Energy Research and Development Division
FINAL PROJECT REPORT

ENERGY INNOVATIONS SMALL GRANT PROGRAM: 2012 INDEPENDENT ASSESSMENT REPORTS

Prepared for: California Energy Commission
Prepared by: San Diego State Research Foundation

SEPTEMBER 2015
CEC-500-2015-074

PREPARED BY*:*

Primary Author:
Rob Queen, Program Administrator

San Diego State Research Foundation
5250 Campanile Drive,
San Diego, CA 92182-1858
(619) 594-1900

Contract Number: 500-98-014

Prepared for:

California Energy Commission

James Lee
Program Manager

Erik Stokes
Office Manager
Energy Deployment & Market Facilitation Office

Laurie ten Hope
Deputy Director
RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Energy Innovations Small Grant Program: 2012 Independent Assessment Reports is the final report for the Energy Innovations Small Grant Program (contract number 500-98-014) conducted by San Diego State University Research Foundation. The information from this project contributes to all of the Energy Research and Development Division's Programs.

When the source of a table, figure or photo is not otherwise credited, it is the work of the author of the report.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Since 1997, the California Energy Commission has been conducting the Public Interest Energy Research (PIER) program through competitive solicitations to advance science or technology in e seven PIER program areas to benefit California ratepayers. In addition, the Energy Commission has also funded and managed the Energy Innovations Small Grant (EISG) Program since 1998

The EISG program supports early phase development of promising new energy technology concepts. This category of projects is not covered by PIER general solicitations, which focuses primarily on developing established concepts. Qualifying EISG projects do fall under one of the defined PIER R&D areas. If the feasibility of an innovative energy concept is proven through the EISG project work, traditional R&D funding may become available to further develop the project.

Independent Assessment Reports are completed for every EISG grant project and outline the objectives of the project, discuss the successes and failures, and offer recommendations for potential future work. This report presents a collection of 20 independent assessment reports for EISG grant projects awarded mostly during 2012.

Keywords: Ratepayer, California Energy Commission, Energy Innovations Small Grant, EISG, Independent Assessment Report, IAR, Public Interest Energy Research, PIER RD&D, electricity, natural gas, transportation, research, energy technology concepts, project, market, outcomes, conclusions, benefits

Please use the following citation for this report:

Queen, Robert (San Diego State University Research Foundation). 2012. *Energy Innovations Small Grant Program: 2012 Independent Assessment Reports.* California Energy Commission. CEC-500-2015-074.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The Public Interest Energy Research (PIER) Program benefits California electric and gas ratepayers by funding energy research, development, and demonstration projects that are not adequately provided for by the competitive and regulated energy markets. Not all of this research, however, is carried out in large corporations or university settings – individuals can have a slice of PIER through the Energy Innovations Small Grant (EISG) program. Managed by the California Energy Commission, the EISG program provides up to $95,000 for hardware projects and $50,000 for modeling projects to small businesses, non-profits, individuals and academic institutions for research that shows the practicability of new, innovative energy concepts. These are promising energy technologies that are not mature enough to be covered by PIER general solicitations and must target one of the PIER Research and Development areas, address a California energy problem and provide a potential benefit to California electric and natural gas ratepayers. Many EISG projects have been successfully commercialized and have leveraged the initial PIER seed funds with additional private or federal funding. Since 1999, the EISG program has awarded more $35 million to over 400 projects. In 2012 (except where noted), the EISG program funded 27 novel projects for more than $2.2 million ranging from innovative wind turbine blade design to advances in electric vehicle charging stations. This report is a compilation of the Individual Assessment Reports for these projects not been previously published

All data sources for tables and figures are from the author unless otherwise noted.

CHAPTER 1: Introduction

In 2012, the Energy Innovations Small Grant (EISG) program funded 20 grant projects for a total of $1.8 million. This report contains the IARs (Independent Assessment Reports) from 2012 EISG projects that have yet to be published. A summary of the funded projects can be found in Table 1.1.

Table 1: 2012 EISG Projects with Individual Assessment Reports

	Researcher	EISG Funding
CPV Module with Zero Cost Thermal Management (2009)	Semprius, Inc.	$95,000
Innovative Blade Design for Next Generation Wind Turbine Blades (2009)	University of California, Los Angeles (UCLA)	$95,000
Stable Fully Distributed Multi-Agent Based Load Management Algorithm for Microgrids (2010)	New Mexico State University	$49,991
Folded Electromagnetic Coil Generator for More Cost-Effective Wind Turbines (2011)	Charles S. Vann	$95,000
Low Cost, Ultra-Thick Electrode Batteries for Grid-Level Storage (2011)	Ballast Energy, Inc.	$95,000
Real-time Cell Assessment Tool (RCAT) for Rapid Estimation of Degradation in the Field (2011)	MODOC ANALYTICS LLC	$95,000
Cloud Based Refrigeration Control System	Visible Energy Inc.	$95,000
Advanced Bioreactor Recycling System for Producing Energy and SNG (2011)	University of California, San Diego	$94,906
Achieving High Efficiencies in Natural Gas Internal Combustion Engines Through Solid State Microwave Assisted Spark Plugs	University of California, Berkeley	$95,000
Electroporation of Algal Biomass to Enhance Methane Gas Production	San Diego State University	$95,000
Low Cost Glazed Polymer Solar Water Heater	Rhotech Solar, LLC	$66,300
Improved Energy Efficiency of Natural Gas/Producer Gas Fuel Mixtures	University of California, San Diego	$95,000

Waste Heat Reformation of Renewable Feedstock to Offset Natural Gas	**Humboldt State University**	**$94,993**
Two-Track Heat Storage: Very Hot Solar Thermal Storage	**Rolf Miles Olsen**	**$94,635**
Earth-Abundant and Scalable Nanostructured Thermoelectrics for Energy Harvesting	**University of California, San Diego**	**$95,000**
Solar Thermoelectric Energy for Residential-Scale Combined Heat and Electricity	**Santa Clara University**	**$94,982**
Adaptive Electric Vehicle Fast Charging Station	**Andromeda Power LLC**	**$95,000**
New Portable Electricity Storage Units Using Nanostructured Supercapacitors	**University of California, Davis**	**$86,476**
Flexible Inverter for Electric Accessories and Export Power in Trucks	**Motiv Power Systems**	**$95,000**
High Capacity Energy Storage for Locomotive Hybridization	**Peaker Conversions**	**$83,383**

CHAPTER 2:
2012 Independent Assessment Reports

The Energy Innovations Small Grant (EISG) program awards numerous grants for innovative energy research projects every year. Independent Assessment Reports (IARs) highlight the project outcomes for each of the EISG projects. This chapter includes the IARs from grant projects that were awarded in 2012 (except where noted) that have not previously been published.

2.1 CPV Module with Zero Cost Thermal Management (2009)

Awardee: Semprius, Inc.

Principal Investigator: Kanchan Ghosal

2.1.1 Abstract

Inadequate management of the thermal energy buildup from concentrated solar radiance has hindered the development of high concentration photovoltaic (HCPV) systems. Current thermal management systems add cost and complexity to systems using HCPV systems. This project evaluated a new approach to HCPV design based on a proprietary printing technology that uses very small PV cells. The researchers proposed using smaller cells to allow distributed thermal dissipation with no additional heat transfer complexity. Thermal models predicted that the copper wire connectors and a metal backplane would be sufficient to dissipate the heat in even very high concentration modules. The primary goal of this project was to validate the thermal modeling performed on the HCPV design with experimental data. The experimental data indicated that modules operated with concentrations of up to 1,000 suns did not need additional thermal management to dissipate the heat generated in the module.

Keywords: CPV, concentrated photovoltaic, micro-transfer printing, transfer printing

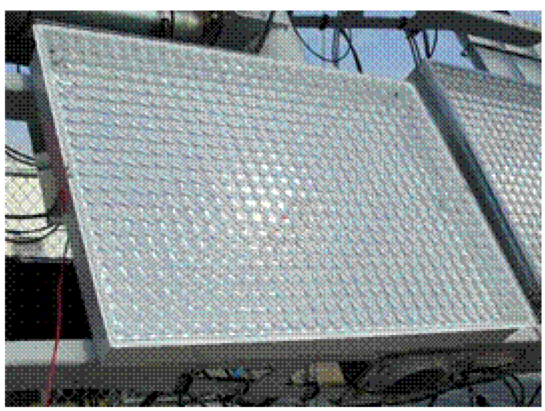
2.1.2 Introduction

Expanded development of renewable energy remains an important focus of California's energy and environmental policies. Increasing the use of photovoltaics (PV) is consistent with this goal. While high concentraton photovoltaics (HCPV) can help meet these policies through more efficient uses of costly PV cell materials, deployment has been hindered by the high heat buildup caused by focusing highly concentrated sunlight onto the cell material. This high heat buildup has demanded complex and costly heat removal systems because cell performance suffers at high ambient temperatures. These challenges drive up cost, complicate operations, and offset much of the cost savings from using less expensive cell materials.

The researchers in this project developed a new HCPV cell design to improve performance, cost, and reliability. They used small gallium arsenide-based cells that are 600 microns per side, in comparison to typical cells that are one centimeter (1,000,000 microns) or larger. Smaller cells have a number of potential benefits. They allow high concentration, shorter optical paths, and passive heat dissipation through the back support. Reliability can be enhanced without using complex heat removal systems by utilizing thin-film metal interconnects and by maintaining low currents and temperatures.

The goal of this project was to validate the previous temperature modeling. Each of the smaller cells needed to dissipate much less heat. However, it was difficult to directly measure the cell temperature to validate the conceptual temperature modeling. The objective of this project was to develop a method for cell temperature measurement, fabricate modules with different sizes and concentrations, and characterize the modules' behavior and performance. Figure 1 illustrates the cell module under testing.

Figure 1: Photo of Microcell Module for 1000 Times Concentration



2.1.3 Objectives

The goal of this project was to validate through experimentation modeling of heat transfer of the new HCPV design. The researchers established the following objectives:

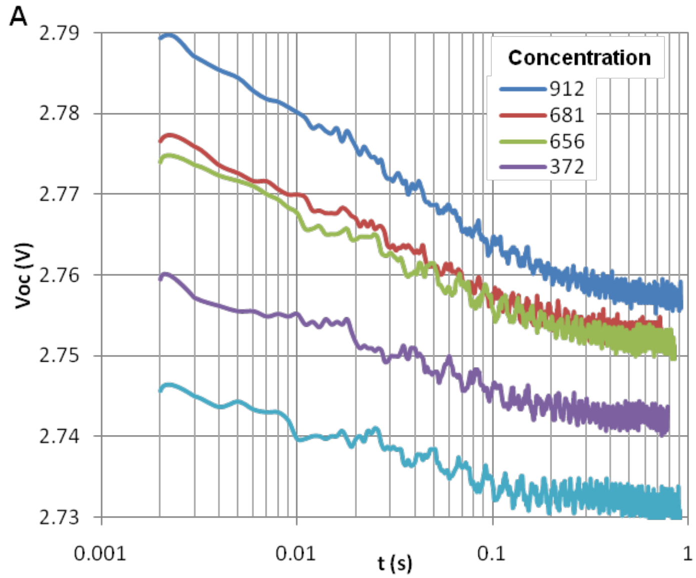
1. Demonstrate that the cell operating temperature (Tc) is correct to +/- 5° C.
2. Verify that Tc <100° C.

3. Demonstrate that the module can operate at 1,000X geometric concentration ratio (GCR).
4. Demonstrate that 2J cell efficiency is >28 percent at 1,000X concentration.
5. Confirm that optical efficiency of the primary lens is >85 percent.
6. Confirm the GCR is 1,000 +/-5.0 percent.
7. Confirm that the short circuit current (Isc) of receivers used in the study are in a +/- 5.0 percent range.
8. Demonstrate that Tc <100° C under a one sun source and standard conditions.
9. Determine the Pmax (maximum power) and module aperture efficiency at 1,000X GCR.
10. Demonstrate power production from the module over the course of one day.
11. Confirm that optical efficiency of primary lens is >85 percent.
12. Confirm GCR is >1,100.
13. Confirm that the Isc of receivers used in the study are in a +/-5.0 percent range.
14. Demonstrate that Tc <100° C under a one sun source and standard conditions.
15. Demonstrate that the Pmax of the module at 1,100X GCR is >7.0 percent higher than the Pmax of the module at 1,000X.
16. Demonstrate that the cost constant is >1 for the module at 1,100X GCR.
17. Determine the optimum GCR for maximizing Pmax/$ ($/Wh).

2.1.4 Outcomes

1. The researchers developed an indirect method to measure cell temperature at operating conditions, based on measuring PV cell performance and the temperature dependence of open circuit voltage (Voc). The researchers claimed that cell temperature could be determined with an accuracy of +/- 1° C. The steady-state temperature dependence of the Voc of a transfer printed microcell has been determined to be 3.6 mV/° C. Figure 2 illustrates the Voc drop as a function of time, due to an increase in cell temperature. The researchers assumed that at the beginning of tests (t=o), the cell temperature (T_c) was equal to the temperature of the mounting equipment, which was maintained at 22.5° C.

Figure 2: Transient Voltage Measurements at Various Geometric Concentration Ratios



2. The researchers measured cell temperature, using the method described in Outcome 1, to be 46° C—53° C at operating conditions.

3. The researchers exposed the cells to 1,000 times the solar concentration (measured as geometric concentration ratio)[1] and determined the module operated as expected.

4. The researchers had the 2J cells tested at the National Renewable Energy Laboratory (NREL). NREL measured cells' efficiency at 31 percent at 1,000 sun solar concentration.

5. The researchers measured the optical efficiency of the primary lens to be 87.5 percent.

6. The researchers calculated the geometric concentration ratio (GCR) to be 987—1,022 times.

7. The researchers built another receiver with a GCR of 1,100 times. The following outcomes refer to the 1,100 GCR receiver:

8. The researchers measured the short circuit current (Isc) of the cells. The mean Isc of the receivers was 0.3009 amps (A). The maximum Isc was 0.0315 A (+4.7 percent), and the minimum Isc was 0.029 A (-3.6 percent).

---

1 The geometric concentration ratio, GCR, is the ratio between the concentrator opening area and the aperture area that receives the solar radiation concentrated by the system. By contrast, the optical concentration ratio gives a truer concentration ratio because it accounts for the optical losses from the reflecting and refracting elements. However, since it has no relationship to the receiver area, it does not give insight into thermal aspects which are proportional to the receiver area.

9. The researchers measured the cell operating temperature (Tc), using the method described in Outcome 1, to be 41.1° C at operating conditions.

10. The researchers measured the maximum module power (Pmax) at 25.6 W at a direct natural irradiation of 954 W/m^2 with a calculated aperture efficiency of 22.9 percent.

11. The researchers measured the power, which exceeded 20 W for the five hours it received direct sunlight.

12. The researchers calculated the optical efficiency of the primary lens to be 88.4 percent.

13. The researchers calculated the GCR to be 1,072—1,152X.

14. The researchers measured the Isc of the receiver to be 0.025 A+/- 2.0 percent.

15. The researchers determined the Tc to be 40.6° C at operating conditions.

16. The Pmax of the 1,100X GCR module was 7.4 percent higher than the Pmax of the 1,000X GCR module, exceeding the target of greater than 7.0 percent.

17. The researchers calculated a cost constant of 1.17. They defined the cost factor as:

    (GCR/1,000)(Efficiency at GCR/Efficiency at GCR of 1,000)*

    The researchers calculated the module efficiency at 24.3 percent for the 1,111X GCR module and 22.9 percent for the 1,000X GCR module. The researchers acknowledged additional improvements in the 1,111 times module that may affect results from optical efficiency enhancement.

18. The researchers calculated the optimum GCR to be 1,111X, based on maximizing Pmax per dollar. They used actual materials cost in their calculations.

2.1.5 Conclusions

1. The ability to measure temperature by measuring cell voltage rather than measuring temperature directly was demonstrated as accurate and precise. The researchers completed this objective.

2. The cell temperature, measured using the method described in Outcome 1, was 46° C—53° C at operating conditions. It is unclear what affect the mounting equipment being held to a constant temperature (22.5° C) had on temperatures and open circuit voltage (Voc) of the cell itself. While the cell measured less than 100° C, the researchers did not achieve this objective, given the confounding issues of mounting hardware temperature.

3. The module operated as expected, under a geometric concentration ratio (GCR) of 1,000 times. The researchers completed this objective.

4. The efficiency of the 2J cells as tested by the National Renewable Energy Laboratory was 31 percent at a 1,000 sun concentration. The researchers completed this objective.

5. The optical efficiency of the primary lens was 87.5 percent. The researchers completed this objective.

6. The calculated GCR was 987—1,022 times. The researchers completed this objective.

The following conclusions refer to the 1,100 GCR receiver:

1. The mean short circuit current (Isc) of the receivers was 0.3009 amps (A). The maximum Isc was 0.0315 A (+4.7 percent), and the minimum Isc was 0.029 A (-3.6 percent). The researchers completed this objective.

2. The cell operating temperature was 41.1° C at operating conditions. It is unclear what affects the mounting equipment being held at a constant temperature (22.5° C) had on temperatures and the Voc of the cell itself. While the cell measured less than 100° C, the researchers did not achieve this objective, given the confounding issues of mounting hardware temperature.

3. The maximum module power (Pmax) was 25.6 W at a direct natural irradiation of 954 W/m^2 with a calculated aperture efficiency of 22.9 percent. The researchers completed this objective.

4. The module's power exceeded 20 W for the five hours it received direct sunlight. The researchers completed this objective.

5. The optical efficiency of the primary lens was 88.4 percent. The researchers completed this objective.

6. The GCR was 1,072—1,152 times. The researchers completed this objective.

7. The Isc of the receiver was 0.025 A +/- 2.0 percent. The researchers completed this objective.

8. The cell operating temperature of 40.6° C at operating conditions, was better than the performance target of less than 100° C. The researchers completed this objective, subject to the caveat noted in Conclusion 8.

9. The 1,100X GCR module had a 7.4 percent higher Pmax than the 1,000X GCR module. The researchers completed this objective.

10. The calculated cost constant of 1.17 was better than the established performance metric of greater than 1.0.

11. The researchers found the optimum GCR to be 1,111 times. Use of actual materials cost improved the determination of optimum GCR. Use of actual fabrication costs under mass production would further improve this calculation. The researchers completed this objective.

The research team validated, through physical measurement, that previous computer modeling of heat transfer under high geometric concentration ratios is valid. Importantly, they demonstrated that complex heat transfer equipment may be avoided while maintaining cell and module temperature under high concentration and achieving high solar efficiency.

2.1.6 Recommendations

The Program Administrator recommends the following actions:

1. Continue to optimize the module for cost, performance, reliability, and higher volume manufacturing. Determine what material choices and manufacturing techniques are necessary to guarantee a minimum 20-year life.
2. Collect data on operating performance of modules deployed into the field as either demonstration or early commercial units and publish that data for use by potential large-scale users.
3. Further develop triple-junction cells (an innovation beyond the dual-junction demonstrated here) using the microcell approach and module configuration, demonstrate the performance and cost benefits, and continue to work toward future generation multiple-junction cells and modules.
4. Resolve the minor issue of temperature impact of mounting hardware used in this test, as described in Conclusions 2 and 8 above.
5. Work with other solar equipment manufacturers (balance of system, tracking equipment, inverters) to simplify overall system manufacture and product marketing.

2.1.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit of this research is increased affordability of electricity in California. As California moves to meet a 33 percent renewable portfolio standard, the potentially achievable $0.10/kWh from this technology would stand in contrast with the approximately $0.15/kWh (and higher) for other renewables (not including federal tax credits). California consumed approximately 200,000 gigawatt hours in 2013. Assuming zero demand growth and achievement of 33 percent of the Renewable Portfolio Standard (RPS) in 2020, the cost of complying with the RPS using this technology rather than the more costly renewables could save California ratepayers over $3 billion per year. Assuming a modest 10 percent penetration of the California renewable energy market, taxpayers would save over $300 million. An additional benefit derives from the flatter output due to tracking, which should reduce the need for backup and balancing of the solar output.

2.1.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG funds.

Marketing/Connection to the Market

Semprius, Inc. is currently working with a number of groups and companies to demonstrate and document cell/module efficiency, including the Electric Power Research Institute, Solar Technology Acceleration Center, Aerojet, and others. Semprius was named one of 2013's 50 Disruptive Companies by *MIT Technology Review*. As the researchers publish the results of these field demonstrations, the market should become more aware of the promise of the technology. Countering this will be stronger competition from traditional energy forms, especially natural gas, as prices continue to drop. This places market pressure on solar in general and on high concentration photovoltaic (HCPV) in particular.

Engineering/Technical

As HCPV systems require accurate and precise tracking equipment, Semprius is working with tracking system manufacturers to improve tracking and cost.

Legal/Contractual

The research team has 30 plus patents, but it is unclear how many of those are specific to the work performed under this EISG project. It also has a number of cooperative working agreements with balance of system and tracking equipment manufacturers.

Environmental, Safety, Risk Assessments/Quality Plans

There are no known unique environmental or safety risks associated with the technology described here. Very large scale solar projects (>~100 MW) using HCPV and other approaches in the desert have raised environmental concerns because of their large footprint, but that would not apply to somewhat smaller projects in urban and suburban settings like parking lots or factory rooftops. Quality assurance plans typical of any technology-centric manufacturing will need to be constantly refined and implemented.

Production Readiness/Commercialization

The HCPV concept described in this research report is being made and commercialized at Semprius' 6 MW manufacturing facility. Further readiness will be focused on evolutionary improvements or next generation cell (e.g., triple-junction) or modules.

2.2 Innovative Blade Design for Next Generation Wind Turbine Blades (2009)

Awardee: University of California, Los Angeles (UCLA).

Principal Investigator: Prof. Richard Wirz

2.2.1 Abstract

As wind turbine blades have grown ever larger in size, the structural stress and strain on blades has increased. This requires improved mechanical strength, especially in the section of the blade nearest the hub. Blade designers have typically used heavier and thicker airfoils, the shape of the blade seen in cross-section, to provide sufficient strength, but that sacrifices aerodynamic efficiency. A new concept, a blade with biplane airfoils, could improve aerodynamic and structural combined performance over that of traditional monoplane blade designs. The technical feasibility of this concept was investigated in this project using simple computational tools. Researchers evaluated the structural performance with finite element analysis. They assessed the aerodynamic performance using a common model and a wind tunnel test. Structural results showed that using biplane cross-sections does not reduce strain, but makes it possible to construct a longer biplane blade. These longer blades would provide larger swept area and therefore greater energy capture. Aerodynamic tests demonstrated increased maximum lift coefficient and aerodynamic efficiency of biplane airfoil sections when compared to typical airfoils. The researchers did not find that these improvements increased power output or the torque necessary for low speed startup. However, they did find that the increased lift of biplane airfoils may make it possible to design a lighter weight blade. In conclusion, improved stiffness and reduced weight enabled by biplane airfoils have the potential to improve the structural performance of wind turbine blades, but significant additional work is required.

Keywords: Wind turbine blades, biplane, joined wing, biplane aerodynamics, blade design

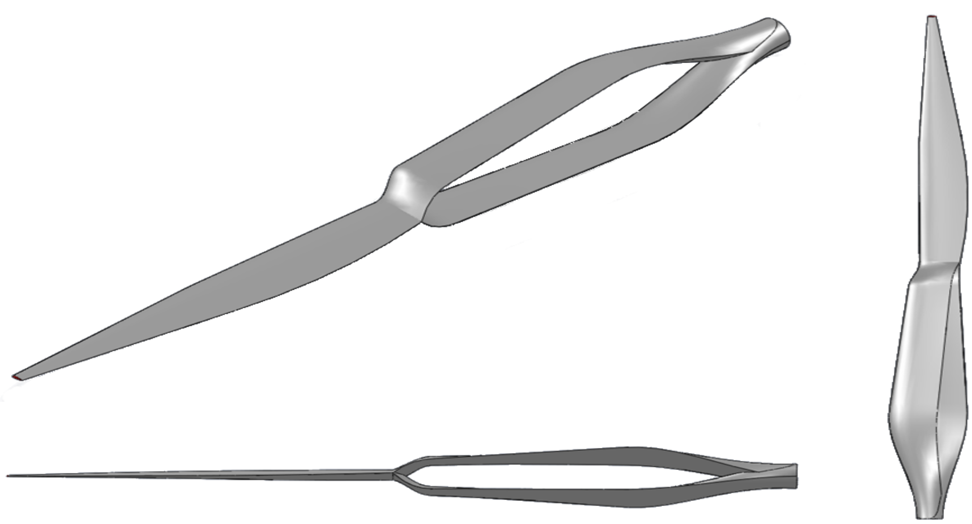
2.2.2 Introduction

Using more and various renewable energy forms remains a priority of California energy policy. One of the fastest growing renewable energy forms is wind energy. Wind turbines are increasing in size with rotor diameters exceeding 120 meters and approaching 140 meters. With the larger diameter rotors, the design requirements have focused on structural performance. Weight and inertia demand great strength in the blade section nearest the hub. This has led to thicker and thicker blades and reduced airfoil efficiency. It has also continued the trend of heavier and heavier blades, increasing the loading on gear boxes and towers. It is conceivable that increased blade length and weight have contributed to the increasing worldwide failure rate of wind turbine blades. The designs of inboard sections are in conflict with strength and aerodynamic performance. For modern large diameter turbines, for example a rotor diameter of ~130 meters, airfoils with thickness ratios approaching 45 percent are used in the hub region to meet structural demands. These thick airfoils suffer from poor aerodynamic performance due to their blunt shapes.

Previous efforts to reduce weight, increase strength, and maintain aerodynamics have explored incremental modifications to thick, yet traditional, airfoil shapes to improve their aerodynamic performance. However, it is possible that only more radical change to the design of blades can simultaneously improve both their aerodynamic and structural performance.

In this project researchers investigated one such novel design, the biplane blade. In this design concept, a biplane section is joined to a monoplane section as shown in Figure 3. By moving weight away from the bending axis of the blade near the hub connection, this design has improved resistance to flapwise bending. The slender profile of the biplane section has improved aerodynamic efficiency compared to the blunt shapes of traditional thick-inboard airfoils.

Figure 3: Drawing of the Biplane Blade



2.2.3 Objectives

The goal of this project was to determine the feasibility of building an improved wind turbine blade using a biplane design. The researchers established the following project objectives:

1. Demonstrate improved aerodynamic performance for higher torque and decreased drag—lift/drag ratio (40) compared to standard inboard airfoils (20). Show improved structural performance of biplane inboard cross-sections: $1.6x10^{-3}$ improved second moment of area, out-of-plane direction, a 20 percent improvement over state-of-the-art blades, assuming a typical 1.5 MW turbine.

2. Demonstrate improved annual energy production (7,680 MWh), 12 percent improvement over state-of-the-art. Demonstrate increased max power generation: 450 kW, 3.0 percent improvement over state-of-the-art. Show improved structural rigidity by demonstrating a one meter or greater increase in blade length (rotor radius) while maintaining constant root strains.

3. Build wind tunnel test article to achieve Reynolds number[2] between 0.7—2 million in wind tunnel facilities.

4. Demonstrate improved aerodynamic efficiency of biplane sections in the inboard region with performance objectives noted in Objective 1. Demonstrate increase in low speed lift required for a startup speed of 4 m/s. Demonstrate total power output increase of 12 percent, thus a cost benefit estimate of 328.5 MWh/turbine/year.

2.2.4 Outcomes

1. The researchers calculated the second moment of area in the out-of-plane direction for the biplane cross-section. Calculations showed about one order of magnitude greater moment than that for the thick monoplane cross-section.

2. The researchers were unable to quantify a direct increase in annual energy production or a direct increase in maximum turbine power output due to the calculated aerodynamic improvements. The researchers concluded that the increased maximum lift coefficient could result in lighter blades with improved fatigue performance, reduced manufacturing cost, and reduced levelized cost of electricity.

3. The researchers fabricated a test article for two-dimensional wind tunnel testing of

2 The Reynolds number measures the ratio of inertial forces to viscous forces and quantifies the relative importance of the two types of forces for given flow conditions. Reynolds numbers frequently arise when performing scaling of fluid dynamics problems, and as such they can be used to determine dynamic similitude between two different cases of fluid flow. They are also used to characterize different flow regimes, such as laminar or turbulent flow. Laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion. Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces which tend to produce eddies, vortices, and other flow instabilities.

biplane airfoil configurations. A Reynolds number of 0.5 million was achieved.

4. The researchers calculated the maximum lift coefficient of a biplane configuration of 2.39 to 2.98 using two 25 percent thick wind turbine airfoils. The researchers neither accurately measured drag nor experimentally determined aerodynamic efficiency (L/D).

2.2.5 Conclusions

1. Calculations by the researchers did not demonstrate any improvement in either energy output or slow speed startup. The researchers did not achieve this objective.

2. For a monoplane beam of fixed length, it is not possible to construct a longer biplane beam with constant root strains. However, it is possible to construct a longer biplane beam with constant tip deflection, that is stiffness. While the researchers did not demonstrate the original objective of maintaining constant root strains, they did show a measure of improved structural rigidity for the biplane blade. The researchers did not complete this objective.

3. The researchers found a Reynolds number of ~500,000 for the biplane design, using wind turbine tests and a mockup blade. The researchers did not achieve this objective.

4. The maximum lift coefficient of a biplane configuration can be as much as 128 percent to 184 percent more than a typical airfoil. Drag measurements from the wind tunnel were inaccurate and therefore an experimental aerodynamic efficiency (L/D) was not calculated. The calculated peak aerodynamic efficiency of the biplane configurations ranged from 56.38 to 80.64, corresponding to a 5.0 percent to 50 percent increase over the aerodynamic efficiency of the 40 percent thick baseline airfoil. The researchers were unable to quantify a direct reduction in startup wind speed due to the improved aerodynamic characteristics of the biplane. The researchers did not achieve this objective.

The researchers have not yet demonstrated the feasibility of using biplane designs to improve the structural and aerodynamic performance of wind turbines.

2.2.6 Recommendations

The Program Administrator recommends that the researchers:

1. Undertake structural analysis and aerodynamic analysis using more complex methods and undertake additional design work. The analysis should also be extended to measure internal stresses, perform dynamic simulations, and analyze buckling modes of the biplane beam, especially in the area of the transition from biplane to monoplane.

2. Undertake additional work to extend the aerodynamic analysis of the biplane sections and consider parameters beyond gap and stagger. The researchers should investigate biplane configuration using asymmetric airfoils.

3. Evaluate the manufacturability of this blade concept.

4. Perform a cost and benefit evaluation that compares the biplane design with more traditional designs.

5. Hold discussions with wind turbine blade manufacturers to assess interest in this concept.

6. Develop a commercialization plan.

2.2.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased affordability of electricity in California.

Assuming the biplane design can be developed to the point of commercialization, it would allow for a larger swept area for a given weight. This would enable higher energy output with lower tower, gear box, and ancillary costs. It should also reduce, by an unknown amount, blade failures. Achieving commercialization should lower the cost of meeting California's aggressive renewable portfolio standard by an unknown amount, given the nascent status of the concept.

2.2.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers had not surveyed potential customers nor had they conducted a market analysis by the end of this project. They had not developed a commercialization plan nor had they contacted any industrial or commercial company about taking this innovation to market.

Engineering/Technical

The researchers had no plans to develop and demonstrate the turbine blade at UCLA nor had they any plans to write an engineering requirements specification.

Legal/Contractual

The researchers have applied for, but they have not yet been granted, United States Patent Application No. 13/581278.

Environmental, Safety, Risk Assessments/Quality Plans

The researchers had no plans to address any of these issues.

Production Readiness/Commercialization

The researchers are looking for possible partner organizations to develop and manufacture the turbine blade.

2.3 Stable Fully Distributed Multi-Agent Based Load Management Algorithm for Microgrids (2010)

Awardee: New Mexico State University

Principal Investigator: Wenxin Liu

2.3.1 Abstract

Micro-grids are small electricity grids that may or may not be capable of autonomous operation. Due to small or distributed sources having less inertia than large thermal power plants, operation and control of micro-grids requires special control strategies and algorithms. One strategy involves managing a load to help maintain a static supply-demand balance within the micro-grid. Distributed load management solutions are an alternative to traditional solutions and can provide acceptable reliability and flexibility. In the researchers' view they are preferable. However, most existing distributed solutions cannot rigorously guarantee convergence and have limited applicability. To overcome these problems, the researchers in this project proposed and evaluated a fully distributed load management solution consisting of a multi-agent system intended to maintain stable micro-grid operations. The team designed a consensus-based global information discovery algorithm that in theory could control systems of arbitrary size and topology and adjust for three generic types of faults. The team also designed an adaptive algorithm to adjust the parameters of the consensus algorithm to maximize convergence speed. The algorithms are described in papers published in *IEEE Transactions*.

Researchers tested the multi-agent solution using both wireless sensor-based and nano PC-based platforms. The researchers simulated the multi-agent system operation of a power system using a real-time digital simulator. Experimental results showed that one round of information status updating could be achieved in about 5 milliseconds and responsive load management decisions could be made in about 0.1 seconds for the five-bus power system that was studied. This indicated that the algorithm had potential to be applied to a range of small power grid optimization and control requirements.

Keywords: Average-consensus theorem, load shedding, load restoration, micro-grid, multi-agent system, real-time digital simulation

2.3.2 Introduction

Grid control methods used for large grids may be costly when applied to micro-grids. Reliance on centralized decision-making entails hardware and software that may be unnecessary and can contribute to reliability and stability problems. Distributed control strategies may be more cost effective and result in improved reliability and stability, thus resulting in faster deployment of distributed energy resources at a lower cost to California ratepayers. This project's research team advanced the science and technology of distributed micro-grid control relying on multi-agent systems.

Applied to micro-grids, this solution may improve reliability and flexibility to accommodate new consumer demands and facilitate integration of additional renewable energy supply. The global information discovery algorithm has the potential for being applied to the design of advanced distributed control and optimization solutions for other problems in power systems.

Faults, sudden load changes, and unplanned generation outages can create power mismatch between generation and loads. If generation in power systems is insufficient to meet instantaneous cumulative demand, load shedding may be required to maintain the supply-demand balance. Load shedding is the process of disconnecting lower priority loads without disrupting the stability of the system that remains active. Likewise, it is important to restore power to the de-energized but un-faulted loads as soon as possible after a fault has been cleared. Timely restoration methods are important to service quality. Restoration may require the investigation of numerous combinations of switching operations.

Centralized control and load shedding for micro-grids that include multiple generators and loads can be accomplished according the same principles as the centralized control of larger grids. Load shedding requires real-time determination of the most appropriate loads to be shed during under-frequency and under-voltage conditions. Distributed control, specifically multi-agent systems, may prove more flexible and adaptive in the context of future California micro-grids that are being powered by ever-increasing numbers of variable distributed sources. Decentralized data processing may enable more efficient and faster automated decision-making.

One of the most popular distributed control solutions is a multi-agent system (MAS). A MAS can accommodate single-point failures. Decentralized data processing can result in efficient task distribution and therefore faster operation and decision-making. However, power system applications require rigorous stability analysis, and applications to date have been limited to radial grid configurations. To demonstrate the applicability of a MAS in more complex structures used for micro-grids, the researchers proposed to investigate a fully distributed MAS-based load management solution. This involves agents making decisions based on the information exchanged among them without the aid of a centralized controller coordinating their activities.

The researchers designed the solution based on a consensus-based global information discovery algorithm that could in theory enable convergence for a communication network of arbitrary topology. In the proposed solution, two agents communicate with each other only if their corresponding buses are connected. Its global information discovery algorithm can bring global situational awareness to the distributed agents, so the information used by the agents for load management will be the same. When the same load management algorithm is used by all the agents, the same load shedding/restoration decisions are made and their load management activities can be coordinated.

The researchers conducted experimental studies to verify the convergence and investigate the real world speed of the load management solution using agents relying on wireless sensors and nano PCs. As shown in Figure 4, the experimental platform under development by the research team, part of which was used in the research reported here, included one real-time digital simulator by OPAL-RT, a real-time amplifier, a MAS, and a renewable micro-grid test bed. The OPAL-RT simulator was Simulink-based and could provide high fidelity real-time simulation. The MAS was able to implement various distributed optimization and control algorithms. The MAS also interacted with power system models simulated in the real-time simulator or directly controlled the physical components in the micro-grid test bed.

Figure 4: Topology of the Experimental Platform for Micro-Grid Study

Multi-Agent System (developed) | **Real-Time Simulator (purchased)** | **Real-Time Amplifier (to purchase)** | **Renewable Microgrid Testbed (under development)**

2.3.3 Objectives

The goal of this project was to determine the feasibility of designing and implementing stable fully distributed multi-agent based load management algorithms for micro-grids. The researchers established the following project objectives:

1. Demonstrate that the three load management problems can be solved together with a MAS-based distributed optimization algorithm.
2. Demonstrate in theory that the global information discovery algorithm is applicable to large-scale systems with arbitrary topologies.
3. Demonstrate in theory that the proposed load management solution is robust under three types of operating conditions, including loss of agent, loss of transmission or distribution line, and change of operating condition during unfinished information discovery.

4. Demonstrate through Matlab and Simulink-based simulations that the proposed algorithm is able to converge within 0.1 second for the IEEE 118 bus system under ideal conditions.
5. Demonstrate that wireless ZigBee sensors-based implementation of the proposed solution is able to converge within 0.1 second for a 10 bus micro-grid.
6. Demonstrate the robustness of the proposed solution under the above three operating conditions through real-time digital simulations using a real-time digital simulator.

2.3.4 Outcomes

To realize project objectives, the research team:

1. Demonstrated through simulations that a consensus-based global information discovery algorithm could bring global situational awareness to the distributed agents using only local communications and that all of the three load management problems, load shedding, load restoration, and reconfiguration, could be solved using distributed control architecture.
2. Analytically demonstrated that, when the topology of the communication network was complete and any two agents could communicate with each other directly or indirectly, a consensus-based global information discovery algorithm could guarantee convergence and thus stability.
3. Analytically demonstrated that loss of a power line and the corresponding communication channel might reduce converging speed, but the algorithm would still converge as long as the post-fault network was still complete. The loss of an agent, generator or load, would reduce the number of communication channels, but the convergence algorithm was still valid. The outdated information discovery process could be identified by checking the converged information vector, and the algorithm could be restarted to avoid inaccuracy.
4. Demonstrated through Matlab and Simulink-based simulations that the proposed algorithm was able to converge within 0.1 second for the IEEE 118 bus system under ideal conditions.
5. Wireless ZigBee and WifiBee sensor-based implementation of the proposed solution demonstrated convergence but not within 0.1 second for a 10 bus micro-grid. The research team solved this problem by replacing the sensors with nano PCs.
6. The PC-based MAS was able, in a simple power system configuration, to interact with the real-time simulator to realize controller hardware-in-the-loop simulation. Experimental results showed that the MAS was able to respond within 0.1 second for a five bus power system.

2.3.5 Conclusions

In general, it seems unlikely that a micro-grid control system in which the only or primary functionality is load shedding and load management will suffice to provide complete automated control and continuous supply/demand balancing. The research consider neither the possible need for the dispatch of flexible generation, charging/discharging of energy storage in normal operations, nor the almost certain need for these controls when the micro-grid may be operating as an island disconnected from a larger grid. As a result, the proposed solution must be viewed as partial or incomplete until integrated with other elements of a micro-grid control system intended for occasional or full-time autonomous operation. Conclusions related to specific objectives and outcomes are as follows:

1. Research results pointed to future distributed control architectures for micro-grids that may incorporate artificial intelligence to make automated real-time load management adjustments. Specifically, they confirmed that three basic load management activities, load shedding, load restoration, and reconfiguration, could, in short-term computer simulations, be accomplished using consensus-based global information discovery algorithms.

2. It could be inferred from idealized simulations conducted by the researchers that such global information discovery algorithms may, in theory, be applicable to large-scale systems with arbitrary topologies. However, the research results demonstrated a mathematical and control concept, not a practical real world application.

3. Success of the proposed distributed control concept would depend on whether the algorithm was solved rapidly and reliably under all foreseeable operational conditions. Physical system faults would impact control algorithm convergence and convergence speed. If convergence were too slow, a cascade of faults might result. Overrides to restart convergence might be required.

4. Simulations demonstrated adequate convergence speed under ideal conditions. However, real world speed would likely be much slower than simulated speed due to the limited utilization of bandwidth, autonomous agent asymmetries, etc. There is a need for experiments to determine how close actual distributed control systems for micro-grids can approach the results achieved under ideal simulation conditions.

5. The researchers learned that use of low cost wireless sensors would not result in adequate convergence speed. The cost impact of needing to use more expensive nano PCs may be an important factor in determining the potential for cost effective application of the proposed control solution.

6. Potential robustness of the proposed solution under the above three necessary load management functions may be feasible but was not demonstrated. That the MAS was able to respond within 0.1 second for a five bus power system was encouraging, but it did not speak to response times for small grids involving hundreds and thousands of buses.

2.3.6 Recommendations

The Program Administrator recommends that further research evaluating a multi-agent based distributed micro-grid control include reference to the control requirements of existing real world micro-grids. For example, the researchers recognized that distributed solar systems feeding into a micro-grid might be numerous, but they did not recognize that they would likely all be responding to the solar radiation and thus would come on-line and go off-line more or less simultaneously. Likewise, the researchers considered sources of power and uses of power but not the energy storage units that would need to account for both sources and loads.

2.3.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is potentially increased affordability of electricity in California to the extent that distributed control of micro-grids enables greater supply contributions from distributed solar PV systems and distributed energy storage systems. The proposed innovation would not create this result without benefit of progress on several other technical fronts, so its benefits cannot be accurately assessed at this time. If it is implemented in the context of an existing micro-grid as suggested above, the results could produce a better estimate of benefits.

2.3.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers did not conduct a market analysis but did review the concept with several naval engineers. The researchers believe the best near-term application of the proposed solution will be micro-grids that have demanding requirements on reliability and survivability, such as naval shipboard power systems.

Engineering/Technical

The researchers predict the solution will be mature in about two years. They stated that they would need about $100,000 to develop an advanced multi-agent system and test it with a micro-grid test bed in the researchers' laboratory.

Legal/Contractual

New Mexico State University filed United States patent application #13/470,801.

Production Readiness/Commercialization

The researchers contacted prospective commercialization partners without receiving a definitive positive response. The best hope for the necessary field test would be an existing micro-grid serving a research organization such as a research university, where the host could take responsibility for securing funds and conducting the necessary tests.

2.4 Folded Electromagnetic Coil Generator for More Cost-Effective Wind Turbines (2011)

Awardee: Charles S. Vann

Principal Investigator: Charles S. Vann

2.4.1 Abstract

The researchers in this project designed, built, and tested a new type of electrical generator with a goal of improving cost effectiveness by 25 percent as measured by power/cost. The new design used circular flux using a folded electromagnetic coil (FEC). This design has received United States Patent number 8,487,486. Advantages over other generators include improved power-to-weight, lower eddy current and core losses, and increased power output.

Researchers constructed a prototype FEC and compared it to a wind turbine generator, Alxion 145STK2M. The FEC generator produced 125 percent more power than the Alxion given the same input torque and resistive loading. The efficiency at the input conditions was the same for both devices, 67 percent. Since the researchers determined the additional generator cost for material and labor would only increase 2.9 percent for the wind turbine, the power-to-cost ratio improved by over 120 percent.

When the researchers adjusted the load from 56 ohms to 12.1 ohms to lower the maximum revolutions per minute (rpm) of the FEC generator to that of the Alxion (325 rpm), the efficiency increased to 90 percent compared to 67.4 percent for the Alxion. The power-to-weight ratio increased by 131 percent.

Additional work is required before the concept is ready for commercialization.

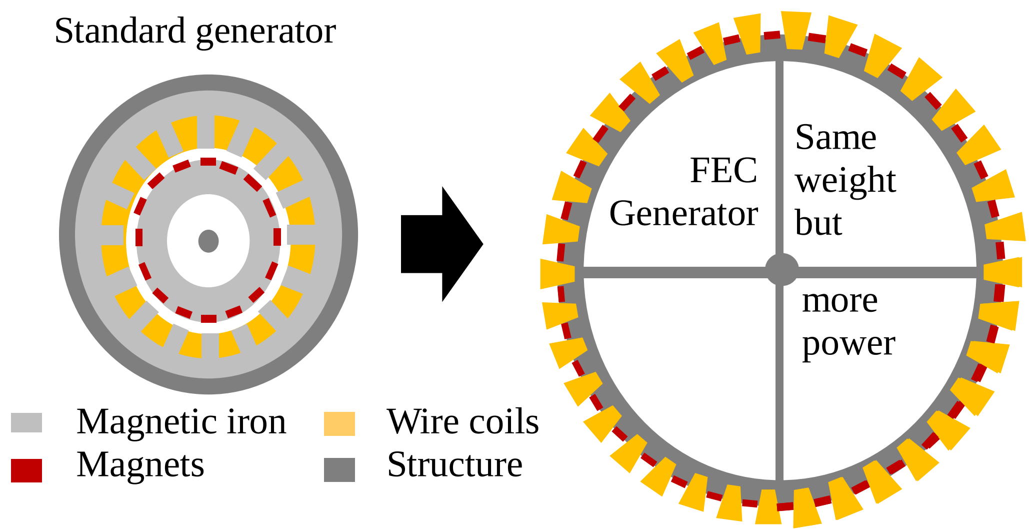
Keywords: Generator, wind turbine, electric power, electromagnetic coil, torque, power-to-cost

2.4.2 Introduction

Expanded development of renewable energy remains an important focus of California's energy and environmental policies. One significant renewable energy form is wind energy. However wind energy remains relatively costly. To reduce costs, every component of wind energy conversion systems needs to improve in cost and performance, including the generator.

The wind turbine generator developed in this project, the folded electromagnetic coil (FEC), can produce significantly more power than a standard wind turbine generator with little loss in efficiency. Most wind turbines are operated at less than optimum efficiency, allowing them to produce additional power. Designers do this because power-to-weight is an important feature for wind turbine generators. The tower can support a limited generator weight, which includes the nacelle, gearbox, and blade weights. If a new generator and a standard generator weigh the same and under the same wind input the new generator produces twice the power, then the entire wind turbine is twice as productive.

Figure 5: Assembled Folded Electromagnetic Coil Generator



The FEC design replaces the heavy, non-productive magnetic iron with productive components (more magnets and wire), increasing power-to-weight and power-to-cost ratios.

In this project researchers designed a new generator arranged in a larger diameter device that used additional magnets and coils and less magnetic iron in the core. See Figure 5. Researchers projected a power increase of 125 percent.

2.4.3 Objectives

The goal of this project was to determine the feasibility of a folded electromagnetic coil (FEC) generator in terms of the power-to-cost ratio. The researchers established the following objectives:

1. Finalize two to four FEC designs.

2. Fabricate and test two to four FEC prototypes.
3. Finalize a generator design with the best FEC.
4. Fabricate generator.
5. Conduct prototype testing.
6. Perform cost analysis of the FEC generator and the benchmark generator.
7. Perform power and cost comparison to determine the power-to-cost ratio of the FEC generator relative to the benchmark and other generators.

2.4.4 Outcomes

1. The researchers developed seven coil designs and computationally and physically analyzed their magnetic flux. Based on that analysis, they developed a current-limiting protective device. The researchers had an outside firm do a finite element analysis on one FEC design.
2. Using information from the finite element analysis, the researchers developed a single best FEC design optimized for seven different design elements: wire gage, magnet size, coil size, spacer type, separation between coils, separation between magnets, and air-gap size.
3. Using CAD, the researchers developed designs and fabricated parts for the generator. They had an outside manufacturer produce the parts.
4. The researchers assembled the generator as shown in Figure 6.

Figure 6: Assembled Folded Electromagnetic Coil Generator

5. The researchers tested the generator and compared it to manufacturer-published performance of the benchmark generator, an Alxion 204 watt model 145STK2M. They calculated an efficiency of 67 percent, similar to the benchmark. They measured higher

power output, at a higher rotational speed (811 rpm versus 325 rpm) but at the same torque (8.9 Nm). At 325 rpm, the FEC generator produced less power, 267 watts, but the researchers determined that the efficiency increased from 67 to 90 percent compared to 204 watts and 67.4 percent for the Alxion.

6. The researchers estimated the cost for the generator and compared it to estimated cost (not price) of the benchmark. They estimated the cost of the FEC generator to be $240 versus $130 for the benchmark.

7. The researchers compared the power-to-cost ratio using their estimated cost and measured power and calculated an improvement in power-to-cost of 121 percent compared to the published power and the cost estimated for the benchmark Alxion.

2.4.5 Conclusions

1. The researchers designed seven generators and completed a flux analysis using computation and physical tests. They designed a required current-limiting device. They had an outside firm complete a finite element analysis. The researchers completed this objective.

2. The researchers selected a single best design optimized to seven different design elements and completed computer-aided design drawings suitable for fabrication. The researchers did not complete the objective of fabricating two to four designs.

3. The researchers completed this objective.

4. The researchers had parts fabricated, assembled the FEC generator, and tested it for power and efficiency. They completed this objective.

5. The researchers demonstrated increased power and efficiency compared to the benchmark at similar rotational speeds. They measured efficiency at 90 percent compared to 68 percent and increased power of 30 percent. The researchers completed this objective.

6. The cost of the FEC was significantly higher than the cost of the benchmark. The researchers completed this objective.

7. Assuming the cost estimates are accurate and performance measurements valid, the FEC provided an improved power-to-cost ratio and improved efficiency. The generator cost increase would make a small increase in overall wind turbine cost but with increased power output. The researchers completed this objective.

The researchers demonstrated the feasibility of their new generator concept, subject to additional verification and testing. Larger scale demonstration will be required for scaling to typical wind turbine sizes in the megawatt range. It is unclear the extent to which rare earth magnets, rather than the design itself, accounted for increased power output.

2.4.6 Recommendations

The Program Administrator recommends that the researchers:

1. Determine and document the amount of power increase due to the incorporation of rare earth (neodymium) magnets versus the design itself.
2. Embark on a program of orderly scale-up to the generator sizes that match the size of typical wind turbines and determine if cost savings in other components, such as the turbine airfoils, result from having a higher generator output. As part of this effort, the researchers should complete a life cycle cost comparison to exiting turbine/generator designs, in terms of the levelized cost of electricity.
3. Use an independent third party to validate performance of their new design over a range of operational conditions, including torque, rotational speed, and load.
4. Evaluate the spoke-and-wheel configuration's mechanical susceptibility to stress fractures that would arise from oscillating torques due to variable wind speeds.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.4.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit of this research is increased affordability of electricity in California. As California moves to meet a 33 percent renewable portfolio standard, the researchers' technology could decrease overall wind turbine costs while improving power output. This cost reduction would benefit wind developers and consumers. Given the early stage of cost estimates and performance characterization, estimating cost savings is premature.

2.4.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

A manufacturer has expressed interest in licensing the technology but has not entered into formal agreements.

Engineering/Technical

Engineering requirements will be developed by firms obtaining licenses to manufacture the new generator (or motors) using this design.

Legal/Contractual

The researchers have filed Patent Applications 12/931,117 and 13/694,949 and received United States Patent 8,487,486 titled Folded Electromagnetic Coil on July 16, 2013.

Environmental, Safety, Risk Assessments/Quality Plans

The researchers will need to work with safety organizations and regulators (e.g., Underwriter Labs) to insure that electrical safety concerns are addressed and that the technology is safety certified or listed once they are closer to production. Quality plans will need to address mechanical stresses as noted above under recommendations.

Production Readiness/Commercialization

The technology is not ready for commercialization.

2.5 Low Cost, Ultra-Thick Electrode Batteries for Grid-Level Storage (2011)

Awardee: Ballast Energy, Inc.

Principal Investigator: Bryan Ho

2.5.1 Abstract

Energy storage is a critical and necessary enabling technology if California is to meet aggressive renewable energy goals and expand cost-effective demand side load-shifting programs. In this project researchers demonstrated the technical feasibility of producing large capacity lithium ion batteries based on a thick electrode design. The researchers' goal was to demonstrate that thick electrodes approximately 1 mm in thickness would deliver the power, efficiency, and lifetime needed for utility-scale energy storage. The researchers confirmed that the novel electrode design could be used to fabricate battery cells that exceed 90 percent capacity utilization and 85 percent round trip efficiency under a five hour charge and discharge rate. Capacity fade due to cycling was well under 1.0 percent over 50 cycles. The researchers used multiple cells to fabricate a full battery but did not complete testing of that battery. The researchers estimated an at-scale cost of $165/kWh and developed a roadmap to reach $150/kWh. The researchers met all objectives except the cost target and battery testing. They must complete significant work and scale-up before widespread grid application of this technology can occur.

Keywords: Lithium, ion, battery, thick electrode, energy storage

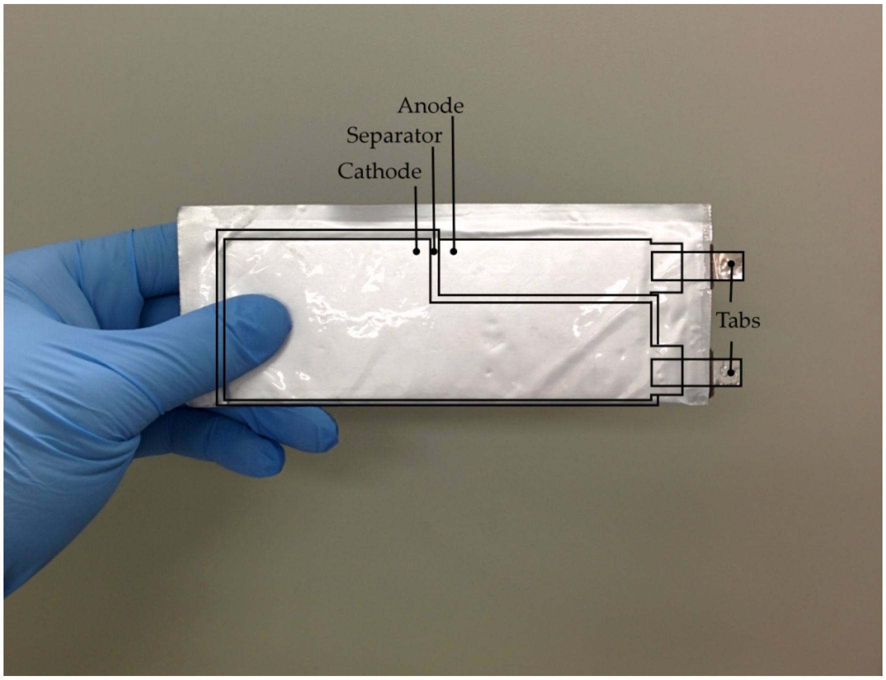
2.5.2 Introduction

Achieving renewable energy targets of 33 percent by the end of the decade may affect the reliability of California's electricity grid. The volatile nature of wind and solar confound the maintenance of frequency and voltage on the grid. While fast ramping gas turbines are being used to address the intermittency of renewable energy, their emissions and fuel consumption offset the benefits of larger amounts of renewable energy. California's recent mandate by the CPUC to install 1.3 GW of storage capacity for increased fast-acting energy storage seeks to address this problem.

Energy storage takes many forms, from mechanical (pumped hydro, flywheels, compressed air, and so forth) to electrochemical (batteries, fuel cells, flow batteries). No single technology has proven superior to another. California's need for energy storage undoubtedly will require multiple approaches, at least in the mid-term. Batteries are one attractive approach, favored for their relatively compact footprint, their ability to be sized for a variety of capacities due to their modularity, and their capacity to receive and deliver power almost instantaneously. Lithium ion batteries may be an enabling technology for energy storage on the grid since they are energy dense, sealed (no hydrogen off-gassing as with lead acid batteries), and have lifetimes that can span thousands of charge/discharge cycles. These characteristics allow siting in urban areas, require minimal maintenance, and provide long lifetimes. The major barrier to widespread adoption of lithium ion batteries for distributed energy storage is their high price. Many current lithium ion batteries are designed for personal products such as cell phones and therefore are very thin.

In this project researchers investigated innovations based on ultra-thick electrodes for batteries to yield cost savings. The cost savings result from reduced chemically inactive materials and fewer current collector and separator films in the battery. Cost reductions also come from reduced capital, labor, and utility requirements since production processes can take advantage of thick and sturdy electrodes rather than delicate, conventionally coated foils. The challenge was to provide sufficient power and lifetime from the battery cells. Figure 7 shows the concept.

Figure 7: Schematic of a Pouch Cell Overlaid on a Photograph



2.5.3 Objectives

This project demonstrated the feasibility of building low cost, large format lithium ion batteries based on an ultra-thick electrode approach. The researchers established these objectives:

1. Demonstrate these performance metrics for ultra-thick cathodes (> 1 mm thick) and anodes (> 0.6 mm thick) in a 10 milli-ampere-hour (mAh) cell:
    - C/5 charge[3] and discharge utilizing > 90 percent of theoretical charge capacity at > 85 percent round trip energy efficiency in a full cell
    - > 85 percent Coulombic efficiency[4] on the first charge/discharge cycle
    - < 3 percent capacity fade over 50 consecutive cycles
2. Demonstrate the three performance metrics stated above for a large area 250 mAh cell.
3. Demonstrate the three performance metrics stated above for a stacked electrode, large area 1,000 mAh cell.

---

3 C isa charge or discharge rate equal to the capacity of a battery divided by one hour. Thus, C for a 1,600 mAh battery would be 1.6 A, C/5 for the same battery would be 320 mA and C/10 would be 160 mA.

4 Coulombic efficiency describes the efficiency with which charge (electrons) are transferred in a system facilitating an electrochemical reaction.

4. Demonstrate less than five percent (± 25 mAh) variability in five consecutively fabricated 1,000 mAh cells.

5. Verify that packaging four 1,000 mAh cells in series within a single casing can produce a two terminal, 12.8 V, 1,000 mAh battery.

6. Demonstrate the three performance metrics stated above for a 12.8 V 1,000 mAh battery.

7. Verify from the project findings that the projected total cost of < $150/kWh, at scale, continues to be supported.

2.5.4 Outcomes

1. The researchers fabricated and tested a 10 mAh cell. Test data were compared to the established performance targets and the results are listed in Table 1:

    - C/5 charge and discharge utilizing > 90 percent of theoretical charge capacity at > 85 percent round trip energy efficiency in a full cell
    - > 85 percent Coulombic efficiency on the first charge/discharge cycle
    - < 3 percent capacity fade over 50 consecutive cycles

2. The researchers fabricated and tested a 250 mAh cell. Test results compared to established performance metrics are in Table 1.

3. The researchers fabricated and tested a stacked electrode, large area 1,000 mAh cell. Measured performance is in Table 1.

Table 1: Target vs. Measured Performance for Three Sizes of Cells

Metric	Target	10 mAh Cell	250 mAh Cell	1000 mAh Cell
Roundtrip energy efficiency	> 85%	91.2%	89.3%	90.1%
First Cycle Coulombic Efficiency	85%	87%	87%	84%
Average Rate of Capacity Loss over 50 Cycles	< 3%	0.2%	0.4%	0.6%

4. The researchers assessed performance variability in five consecutively fabricated 1,000 mAh cells. The five consecutively fabricated 1,000 mAh cells showed a maximum 3.6 percent cell-to-cell variability and nearly identical discharge voltage curves.

5. The researchers combined four cells, each 1,000 mAh, in series in a single casing to produce a two terminal, 12.8 V, 1,000 mAh battery. Each cell had a voltage of 3.27 V,

combining to produce a battery of 13.07 V.

6. The researchers did not measure rate capability, first cycle Coulombic efficiency, or capacity loss for the 12.8 V 1,000 mAh battery.

7. The researchers estimated the manufactured cost of cells based on the ultra-thick electrodes to be $165/kWh.

2.5.5 Conclusions

1. Thick electrodes can be used to fabricate 10, 250, and 1,000 mAh battery cells using lithium ion electrochemistry. These cells can achieve high charge/discharge efficiency and relatively low charge fade over at least 50 cycles. The researchers achieved, or nearly achieved, Objectives 1, 2, and 3.

2. Assuring quality performance is promising. The performance in five similarly fabricated 1,000 mAh cells showed low and acceptable variability. The researchers achieved Objective 4.

3. Connecting several cells in series to produce a battery of nominal voltage (13.1 V) with two terminals is practical from a technology standpoint, subject to Conclusion 4 below. The researchers achieved Objective 5.

4. The researchers did not measure the performance of the fabricated 1,000 mAh battery. They did not complete Objective 6.

5. For an initial effort, cost estimates were close to target costs. Further development and optimization may achieve costs nearer the target. The researchers completed but did not achieve Objective 7.

The researchers demonstrated the technical feasibility of using thick electrodes in lithium ion electrochemistry-based batteries. They have not yet demonstrated feasibility in utility-scale application or practicality from a cost standpoint.

2.5.6 Recommendations

The Program Administrator recommends that the researchers:

1. Continue optimization and scale-up of the ultra-thick electrode design.

2. Determine if the thick electrode has unique memory issues compared to other battery configurations and develop a battery management protocol if necessary.

3. Develop temperature management schemes and designs for large-scale installations to safely handle MWh charge/discharge cycles, especially for those rapid cycles used in balancing intermittent renewable generation.

4. Determine the impact of charge/discharge rate on performance.

5. Determine battery lifetime in a number of discharge cycles. Also determine battery degradation in utility service.

6. Continue efforts to reduce costs below the target of $150 kWh. In conjunction with this activity the researchers should compare their expected all-in cost for energy storage with costs on the newly established energy imbalance market and other capacity values.
7. Design production processes to move from laboratory scale to pilot scale production and ultimately to commercial scale. The researchers should work with commercial firms in the lithium ion battery market to develop and modify battery-manufacturing methods for use with their design.
8. Work with utilities and grid operators to develop specific engineering requirements and technical specifications of the battery and control equipment and work with certification agencies for listing.
9. Benchmark competing technologies such as flow batteries and possible new batteries based on magnesium ions.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.5.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit of this research is increased affordability of electricity in California. The California Public Utilities Commission has mandated that 1.3 GW of energy storage capacity be introduced in the state by the year 2020. Such a large-scale requirement for energy storage requires that major cost improvements for storage options occur lest ratepayers experience rate shock. Researchers in this project were aiming for cost reductions for lithium ion cells of over $100/kWh. Assuming that 50 percent of the 1.3 GW of mandated storage capacity is from lithium ion batteries, this technology could save $130 million in capital costs for implementing the storage mandate, compared to other lithium ion technologies. Compared to other battery technologies, the savings would be even larger, since traditional batteries have shorter lifespans and need frequent replacement. Even at equal installed cost of $150/kWh, lithium ion batteries would provide capital cost relief by avoiding recurring replacement costs.[5] Additionally, operational savings would accrue from less expensive solutions to balancing intermittent renewables and from more efficient load shifting demand-side programs.

2.5.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have discussed commercializing the technology with a major battery manufacturer, but they have not reached a formal agreement. The researchers will need to collaborate with utilities and grid operators in defining battery performance and connection requirements. They will need to work with certification agencies (e.g., Underwriter Labs) to have the technology package listed, especially for residential and commercial application.

Engineering/Technical

Engineering requirements for grid interface and battery management will need to be developed. Packaging design needs to consider thermal management and perhaps communications and control systems. Interconnection requirements are being developed jointly by Cal ISO, the Energy Commission, and CPUC for energy storage systems.[6] Charge and discharge rate limiters may be needed.

Legal/Contractual

The researchers have applied for, but they have not received patent protection**.**

Environmental, Safety, Risk Assessments/Quality Plans

There are no unique environmental or safety risks associated with this technology. The researchers will need to develop quality assurance plans as production scales up from laboratory to commercial production.

Production Readiness/Commercialization

The technology is ready for scale-up to pilot scale production for further testing, demonstration, and development, but it is not yet ready for commercialization.

5 http://theenergycollective.com/schalk-cloete/421716/seeking-consensus-internalized-costs-energy-storage-batteries

6 http://www.cpuc.ca.gov/NR/rdonlyres/E02F0CD0-170A-4529-BE74-6F0A8DC416D3/0/Roadmap_Oct9_FINAL.pdf

2.6 Real-time Cell Assessment Tool (RCAT) for Rapid Estimation of Degradation in the Field (2011)

Awardee: Modoc Analytics LLC

Principal Investigator: Abe Ishihara

2.6.1 Abstract

This project was to build a working prototype of a real-time cell assessment tool (RCAT) that could be used in the field to rapidly detect PV module degradation and failure. The researchers built a working prototype for the RCAT and tested it in a field setting. The prototype involved the use of a polymer dispersed liquid crystal screen capable of selectively shading a single solar cell. The researchers collected pairs of I-V capture curves for every solar cell within a module. One capture was taken for the entire module with a single cell selectively shaded, and one capture was taken without any shading. The researchers analyzed the I-V capture pairs to identify cells with diminished shunt resistance, an indicator of poor performance and power loss. They performed testing of a single 36 cell Kyocera KC50T module in approximately 18 minutes. Results were consistent with validation testing using alternate testing methods, including electroluminescence and thermal history. Using 2012 installation data, the researchers estimated that California ratepayers could recapture up to $1.33/W in saved energy cost over the life of the system by identifying and replacing faulty solar cells.

Keywords: PV module degradation, detection of PV failure modes, PDLC, smart glass, system identification

2.6.2 Introduction

Solar initiatives have become a statewide and nationwide priority in recent years. Rebates and incentive programs have led to rapid and widespread adoption of solar energy in both residential and commercial settings. Advancements in solar technology have been successful in improving PV module reliability and efficiency while reducing costs. However, little research has been conducted to evaluate ongoing performance of solar panels once they are assembled and operational.

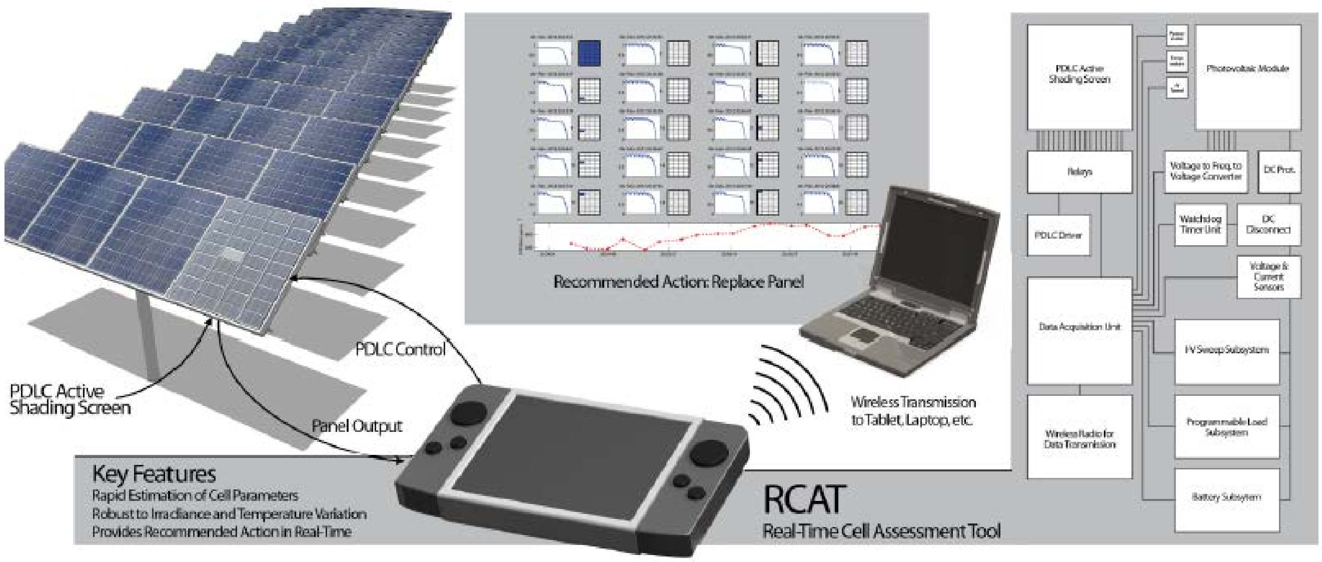
Solar panel performance can degrade as a result of faulty modules or environmental stresses, such as shading or debris accumulation. Environmental stresses are more readily recognized and rectified than module failure. A case study referenced by the author found that field inspectors failed to identify any defects in an installation while the research team's testing indicated a 50 percent failure rate for the solar cells.

There are a number of cell degradation assessment methods available, including electroluminescence, photoluminescence, lock-in thermography, light-beam induced current, and IMS shading. However, few of these methods give quantitative information as sunlight-electrical power conversion, and few are suitable for field operation at a reasonable cost.

The researchers prototyped and tested a real-time photovoltaic cell assessment tool (RCAT) capable of detecting cell degradation in a field setting (Figure 8). Cell degradation can be evaluated by quantifying shunt resistance (Rs) and identifying those cells with a decreased resistance as candidates for replacement. Photovoltaic cells with high Rs deliver a larger fraction of the power generated by the cell, minimize pathways through which power is permitted to recirculate within the cell, minimize heat generated by the dissipated power, and resist the possibility of thermal runaway. Thermal runaway is a phenomenon whereby increased heat leads to increased power dissipation, which then leads to additional increases in heat, resulting in a vicious cycle and ultimately module failure.

The researchers anticipated that the RCAT could be used to save $1.33/W in energy costs over the life of a 4 kW residential solar system as a result of identification and replacement of faulty solar cells. Savings were estimated considering an average installed system cost of $6.97/W and failure rate of 16 percent. The testing cost would be approximately $0.50/W, resulting in a net savings to the ratepayer of $0.83/W for a typical 4 kW system. Applying the same methodology to current installed system costs of $5.53/W, results in a net savings of $0.75/W for a typical 4 kW residential system.

Figure 8: Real Time Cell Assessment Tool (RCAT)



2.6.3 Objectives

The goal of this project was to build a working prototype of a real-time cell assessment tool (RCAT) that could be used in the field to detect PV module degradation and failure rapidly. The researchers established the following project objectives:

1. Ensure the parameter extraction method converges rapidly within three seconds to a solution.
2. Ensure the I-V curve estimate is generated within three seconds.
3. Validate that algorithms determine degradation within 4.0 percent accuracy.
4. Validate that environmental variations change results by no more than 2.0 percent.
5. Demonstrate that the degradation of a string of modules can be assessed.
6. Demonstrate that the environment changes cause less than 2.0 percent change in extracted parameters.
7. Confirm the I-V curve capture, agreeing within +/- 2.0 percent of baseline voltages and currents within 30 seconds total cycle time.
8. Prove that the algorithms can estimate the probability of failure within one minute.
9. Demonstrate that the cell characteristics and anomalies can be identified within 15 minutes.
10. Identify design flaws and weaknesses.

11. Validate that the tool gives no more than 6.0 percent difference when employed outdoors compared to a laboratory setting.

12. Validate the projection of total amount of $1.33/W in saved energy costs over the life of the system due to identification and replacement of failed and/or degraded past warranty PV modules.

2.6.4 Outcomes

1. The parameter extraction method converged in 0.72 seconds.

2. I-V curve estimates were generated in 0.94 seconds, using 100 uniform steps in voltage between 0-V and open circuit voltage.

3. The researchers measured degradation of shunt resistance (Rs) as the difference between the estimated and nominal values, divided by the nominal. The estimation approach was only able to determine the shunt resistance within 25 percent of the actual value. The error was attributed to an assumption that all remaining cells in a module are uniform, whereas in simulations the shunt resistance was taken from a Gaussian distribution about a given mean.

4. The researchers simulated environmental settings by changing temperature and irradiance. System identification did not change by more than 1.0 percent of the baseline. Although the researchers considered temperature impacts on photo current and reverse saturation current, the system identification procedure estimated these values, regardless of the temperature or irradiance. The researchers assumed Rsh and Rs were independent of temperature and irradiance. Although this is a common assumption, there are studies that include temperature and irradiance dependency for Rsh and Rs.

5. The researchers connected six modules in a series. They found processing time per module was 18 minutes, and RCAT analysis time was approximately 48 minutes.

6. The method used to determine the impact of environmental changes is unclear. The researchers determined that 90 percent of parameter estimates of each individual cell did not vary by more than 2.0 percent. Although the researchers' results lacked detailed labels and information needed for interpretation, it appears that the remaining 10 percent of the parameter estimates varied by approximately 24 percent.

7. Data capture included in the I-V curve capture pairs for each cell in the solar module were performed in rapid succession. The researchers performed the first capture while selectively shading a single cell. They performed the second capture without any shading on the module. This process was repeated for each cell. Completion times varied between 22.4 and 24.4 seconds.

8. The researchers defined failure as a 50 percent reduction in shunt resistance. The researchers acknowledged that this assumption had not been validated. Thus this objective could not be completed without additional research.

9. Data collection required less than 14 minutes.
10. The researchers identified browning of the polymer dispersed liquid crystalscreen as the primary design flaw.
11. The researchers were unable to perform laboratory testing for validation.
12. Using data published in 2012, the researchers estimated the cost of an average 4kW residential solar system was $6.97/W. Published field studies indicate that 16 percent of all installed residential panels needed replacement before the end of the projected system life. Defective panels render the system 16 percent less productive (3.36 kW), which results in effective installed cost of $8.30/W. The real-time cell assessment tool would enable detection of defective cells to prevent this loss of $1.33/W. The researchers estimated the cost of the tool as $0.50/W, resulting in a net savings of $0.83/W using the tool. This same calculation using current solar installation cost estimates results in a net savings of $0.75/W.

2.6.5 Conclusions

1. The researchers met the objective to extract parameters within three seconds. The rapid convergence in 0.72 seconds would assist in user acceptability in a production setting.
2. The researchers met the objective to generate I-V curves within three seconds. Rapid curve generation will similarly assist in user acceptability in a production setting.
3. The researchers were not able to meet the objective to determine degradation within 4.0 percent accuracy. This is a critical objective that will require additional research to achieve. Inability to meet this objective renders the real-time cell assessment tool (RCAT) qualitative at best and does not allow market differentiation as a quantitative tool, as originally conceived.
4. The researchers did not meet the objective to validate that environmental variations did not change the results by more than 2.0 percent. The approach was fundamentally flawed. Given the assumption that estimated values are independent of temperature and irradiance, it is not too surprising that these factors did not impact the estimated results. The purpose of this objective was unclear.
5. The researchers met the objective to assess modules configured in series.
6. The researchers did not meet the objective to demonstrate that environmental changes caused less than 2.0 percent change in extracted parameters. This appeared to relate to the inability to quantitatively measure shunt resistance, as discussed under Objective 3.
7. The researchers met the objective to perform I-V curve capture within 30 seconds.
8. The researchers did not complete the objective to estimate the probability of failure within one minute. Further research will be needed to establish failure criteria.

9. The researchers met the objective to identify cell characteristics and anomalies in less than 15 minutes.

10. The researchers partially met the objective to identify system design flaws and weaknesses. Browning is considered the only weakness of consequence, and the researchers intend to further research materials for this purpose. However, the researchers state this weakness is not likely to impact the use of the RCAT. Challenges relating to portability, adaptability, and quantification of shunt resistance are the true weaknesses of this system and the determining factors for commercial viability.

11. The researchers did not complete this objective.

12. The researchers met the objective to demonstrate a total cost savings of $1.33/W, exclusive of costs to use the RCAT.

2.6.6 Recommendations

The researchers were successful in demonstrating using the real-time cell assessment tool (RCAT) in a field setting. The researchers acknowledged the need for design enhancement to permit portability and adaptability to a wider variety of solar modules. A more flexible design would further enable laboratory testing of the RCAT. The researchers have captured an important niche that will become increasingly more necessary with the rapid adoption of solar technology. Although the tool is likely to be useful in performing a qualitative assessment of solar cell degradation, it would be even more useful as a quantitative tool. Therefore the ability to accurately evaluate shunt resistance should be a research priority. The Program Administrator recommends that the following tasks be completed:

1. Refine the approach to shunt resistance determination to allow achievement of Objective 3. Without a more accurate determination, this tool may still be valuable. However, it will not be able to differentiate itself easily from other existing qualitative assessment tools.

2. Consider temperature and irradiance impact on Rsh and Rs.

3. Research and establish the criteria for determination of cell failure.

4. Iterate on the screen configuration to improve portability, flexibility, and adaptability to a wide range of installations.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.6.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The researchers estimated a net cost savings of $0.83/W using 2012 solar installation cost data, as described in Objective 12. The cost savings is $0.75/W using the same methodology with current cost data.

2.6.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have not yet performed a market analysis. The market includes commercial, residential, industrial, and utility solar installations.

Engineering/Technical

Additional prototype iterations are needed to improve portability, flexibility, integrity, and adaptability. The iterations are anticipated to cost approximately $50,000 and will take two years to complete.

Legal/Contractual

The researchers have performed a self-search and filed a provisional patent for this technology.

Environmental, Safety, Risk Assessments/Quality Plans

The researchers do not anticipate any negative effects with regard to public safety or the environment.

Production Readiness/Commercialization

The technology is not yet developed sufficiently to pursue commercialization. Once the proof-of-concept work is complete, the researchers will require assistance to go to market.

2.7 Cloud Based Refrigeration Control System

Awardee: Visible Energy Inc.

Principal Investigator: Marco Graziano

2.7.1 Abstract

The goal of this project was to verify the feasibility of operating a commercial refrigerator in the cloud by ensuring proper functioning of the refrigerated appliance. The researchers demonstrated how the cloud could be used to incorporate power consumption in the refrigerator control method, as well as its scalability for industrial use. The researchers developed a prototype controller and web-based software capable of retrofit in existing refrigeration systems. They estimated the material cost for the hardware to be $52 in quantities of 10,000, slightly more than the targeted $50 per unit. The researchers tested the cloud architecture in a simulated environment to manage 1,000,000 simultaneous connections. They performed field testing using a single installation in a reach-in refrigerator in Palo Alto, California. Test results indicated the controller was capable of maintaining a cabin temperature between 3° C and 7° C using a simple hysteresis control methodology. The researchers were able to demonstrate a 22 percent energy savings over the baseline factory thermostat using the simple hysteresis loop. Improvement of the control methodology to account for daily usage, peak activity, and idle periods resulted in additional energy savings amounting to 60 percent over the factory thermostat.

Keywords: Refrigeration, cloud computing, energy conservation, smart controller, refrigeration energy consumption, refrigeration control, demand response

2.7.2 Introduction

Commercial refrigeration consumes 14 percent of all energy within the commercial sector, and the bulk of this usage is in the food industry. In California there are over 110,000 commercial establishments that use refrigeration equipment. Typically commercial refrigerators operate using established set points monitored by a factory-installed thermostat without regard to usage or energy consumption.

The researchers proposed to bypass factory controllers and port refrigeration control in favor of a cloud-based computing environment. Sensors installed in the refrigerator-collected data on power consumption and ambient temperature. Installed controllers remotely operated the compressor, evaporator fan, and defrost element. The researchers analyzed sensor data and used this for the operating system that remotely executed the refrigeration control loop. Refrigeration was provided using a simple hysteresis control loop with an upper and lower temperature bound. The proposed Cloudfridge included development and testing of hardware to collect data and software to analyze collected data and execute the control loop remotely.

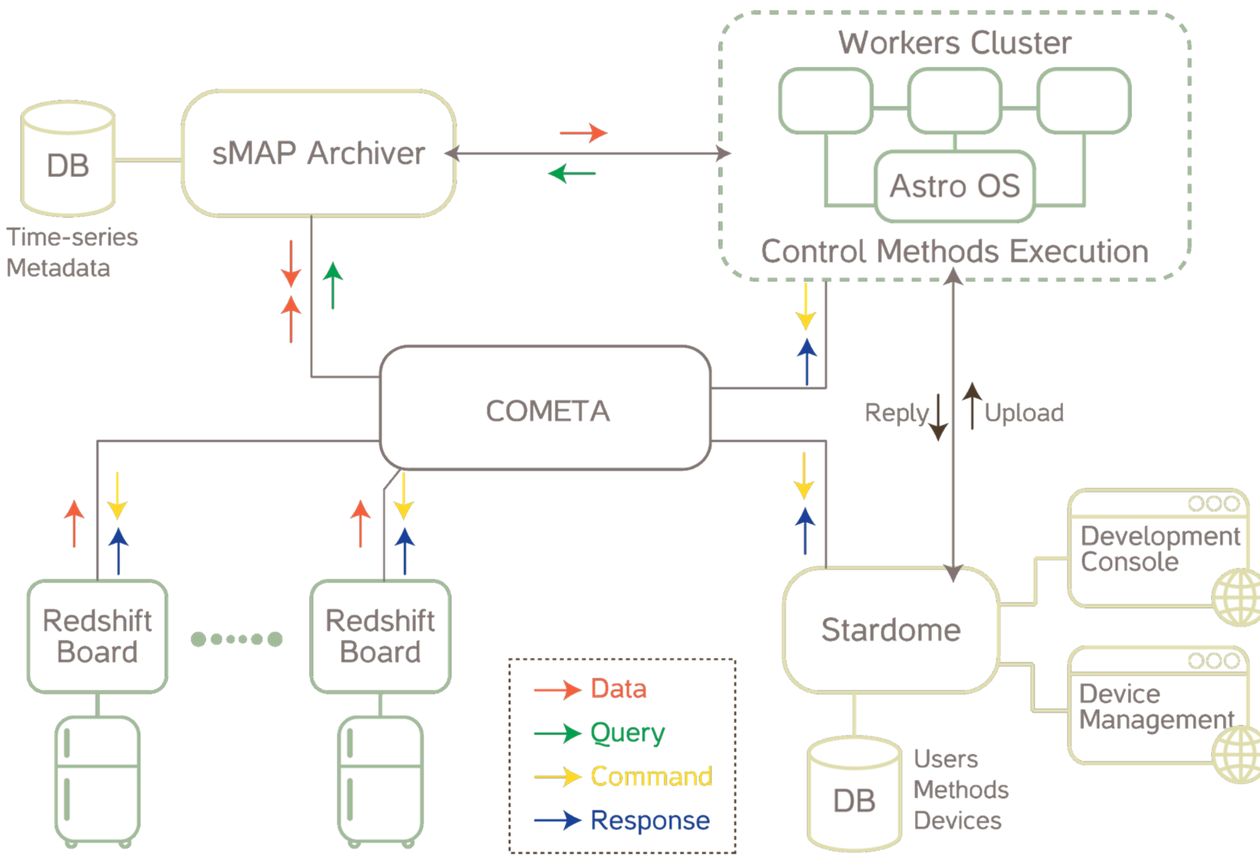
The researchers designed and prototyped a Redshift board which contained an actuating component, a measuring/sensing component, and a communicating component (Figure 9). The actuating component was responsible for operating the compressor, fan, defroster, and lights. The measuring/sensing component captured temperature, humidity, door opening, and power usage data. The communication component allowed the data to be transmitted to a cloud computing environment using Wi-Fi technology.

The researchers developed software using a distributed architecture and included a number of proprietary components (Figure 10). The Cometa Cloud Platform allowed for real time communication between an application server and the remote devices. The sMap Archiver Data Repository provided the database used to store relayed data. Astro was the operating system that performed computations on data and execution instructions for the control loop. Stardome was the application server that interacted with the Redshift board to operate actuators and sensors. Operation of the Cloudfridge system required significant expertise in refrigeration control methodology and computer programming to design a control loop strategy and codify the method using the Astro operating system syntax. The researchers indicated that Cloudfridge would be a subscription-based service with approximately a $20 annual fee. Presumably this fee would include design and coding of the control loop.

The researchers were able to demonstrate a 22 percent energy savings over the baseline factory thermostat using the simple hysteresis controller. Improvement of the control methodology to account for daily usage, peak activity, and idle periods resulted in additional energy savings totaling 60 percent over the factory thermostat. Assuming a 50 percent energy savings, the researchers estimated annual savings of $200 to $250 per unit using Cloudfridge.

Figure 9: Laboratory Refrigerator Retrofitted with a Redshift Board

Figure 10: Cloudfridge Software Components



2.7.3 Objectives

The goal of this project was to verify the feasibility of operating a commercial refrigerator in the cloud by ensuring proper functioning of the refrigerated appliance. The researchers included a demonstration of how the system would be used to incorporate power consumption in the control method and its scalability for industrial use. They established the following project objectives:

1. Demonstrate communication and the control board with a response time on the order of a few hundred milliseconds when communicating with a cloud server. The bill of materials (BOM) should cost less than $50 in volume. Assess the worst case response time with a typical broadband connection.
2. Develop a test suite to validate the software and software tested against it. Compose the test suite of test units written to verify proper operation of the cloud operating system software application programming interfaces (APIs), each defined to assess whether a certain function in the API passes or does not pass the test.
3. Confirm cabinet temperature will remain within +/- 1° C of the set point for continuous operation for at least one week.
4. Demonstrate through a test bench refrigerator and a simulation of remote interactions that industrial-scale deployment of the implemented cloud operating system is feasible.
5. Verify the ability of the system to sustain a simulation to reproduce the workload typical of 100,000 connected refrigerators. Verify the ability of the system to keep the temperature of the test bench refrigerator within +/- 1° C of the set points while operating at least 10,000 simulated remote refrigerator units.
6. Achieve at least 5.0 percent energy consumption reduction in a refrigerator with typical baseline energy consumption of 3,960 kWh/year.

2.7.4 Outcomes

1. The researchers designed, prototyped, and installed a Redshift board in a Beverage Air KR74-AS reach-in refrigeration unit at the Caffe Riace restaurant. The board included components for actuating, measuring/sensing, and communicating using Wi-Fi technology. The average latency for a data acquisition request/response exchange of 1,000 messages was measured as 681 milliseconds, including time needed to acquire data from sensors and time needed to communicate between the Cometa server and Redshift board. The researchers noted that at least 50 percent of this time was spent by the Redshift firmware to acquire data from the connected sensors. The researchers estimated the time needed to acquire data from the sensors might take up to 400 milliseconds. However there were no measurements to support either of these claims. A cost estimate provided by Weistech Technology indicated a Redshift board manufacturing cost of $52.30 for quantities of 10,000 units.

2. The researchers developed application programming interfaces (APIs) for the following software components:

    - Redshift Firmware JSON
    - Cometa back end
    - Stardome application server
    - Astro OS virtual refrigerator operating system
    - sMAP archiver

    Test plans to address each API were not developed as proposed. Instead integrated testing was applied incrementally in parallel throughout development to permit the rapid development cycle seen as essential to attaining the goal. The validation of each constituent software element was thereby established at the unit level and subsequently at the whole system level. Referenced incremental and system test plans were not presented nor were results of the tests. The researchers presented published accuracy data for the temperature sensor but presented no testing, validation of accuracy, or calibration for this or any other sensors or components used in the Redshift assembly.

3. The researchers ran a continuous field test of Cloudfridge at Caffee Riace. The researchers stated that the test was run for one month, but graphical data were presented only for September 10 to October 1, which nevertheless exceeds the goal of one week of continuous operation. They established the set points as 2.5° C and 7° C initially, and then 3° C and 7° C four days into the test. They took cabin temperature readings every minute. The researchers attributed elevated spikes to prolonged door opening events. Subzero spikes were attributed to correction of prior peaks.

4. The researchers tested the Cometa server architecture using 1,000,000 simulated connections. They verified connections by pinging simulated devices and recording the response. To overcome connection limitations inherent in UNIX systems, the researchers initiated 19 separate client applications, each connecting to 55,000 simulated devices.

5. This task was not performed.

6. Preliminary energy measurements of the Caffe Riace refrigerator using an energy meter at the power socket indicated a power usage of 80 kWh/week with the factory-installed thermostat. Researchers took measurements in the month of August. Testing of the retrofit refrigerator indicated usage of 62.63 kWh/week using a simple hysteresis loop control method. Modification of the control algorithm to adjust for standard daily usage, peak activity, and idle periods resulted in a usage of 31.70 kWh/week. The researchers took Cloudfridge measurements in the month of November.

2.7.5 Conclusions

1. The researchers did not meet the goal to demonstrate a control board response time on the order of a few hundred milliseconds and assess worst case response time, but they

nearly met the goal to demonstrate a BOM estimate of less than $50. The response time of 681 milliseconds was approximately twice the original target value, which failed to discriminate between sensor data acquisition delay and communication latency. In any case, the researchers' claims regarding sensor data acquisition delay were unsubstantiated. They did not perform a sensitivity study or statistical analysis to assess worst case response time as proposed. Although the cost estimate was slightly higher than the project goal, the researchers anticipated that oversized components could be customized and optimized to gain a 20 percent cost reduction.

2. The researchers did not meet the goal to develop a test suite to validate the software and test against it. This step was bypassed in favor of full-scale development, with the presumption that output validated performance without regard for accuracy of the output. Because temperature regulation and energy consumption were key to successful operation of the control loop, it is surprising that the researchers failed to test or calibrate these or any other sensor integrated into the Redshift board. When queried by the Technical Reviewer regarding data uncertainty, the researchers indicated, "There are no uncertainties in data acquired from the power sensors and the temperature sensors." Although a convenient theoretical assumption, this is a scientific impossibility.
3. It is unclear if the researchers met the goal to maintain cabinet temperature within +/- 1° C for one week of continuous operation. Neither raw data nor statistical analyses were presented for actual data compared with temperature set points. Graphically presented data appeared to be in compliance with the project goal, but the scale of the graph and lack of actual data or error analysis made it difficult to verify conclusively that the goal was met.
4. The researchers met the goal to demonstrate industrial-scale deployment of the cloud operating system. However, aside from noting that over 1,000,000 connections were established, the researchers collected no data regarding latency, bandwidth requirements, impact on performance, or other effects of scaling to industrial deployment.
5. The researchers did not meet the goal to reproduce the workload typical of 100,000 connected refrigerators.
6. The researchers met the goal to achieve at least 5.0 percent energy consumption reduction. Control using the simple hysteresis loop resulted in a 22 percent reduction, and further improvements in the control methodology resulted in a 60 percent reduction. Although the goal was surpassed, the researchers did not address the impact of ambient temperature fluctuations on energy consumption. They measured the control during the warmest month of the year, and they performed the field tests near the coldest month of the year. The timing of the measurements introduced another variable to the analysis that either needs elimination or further investigation.

The researchers met approximately half of the project objectives. The study successfully demonstrated potential energy savings using Cloudfridge.

2.7.6 Recommendations

This project would benefit from a more rigorous, scientific methodology in data acquisition and assessment. Further, although the proposed technology clearly has merits, the feasibility of its implementation among a non-technical user base is questionable. There are also significant concerns with regard to how fail-safe Cloudfridge is in case of internet connectivity loss. As a part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Investigate alternatives to accommodate connectivity loss, including reversion to factory-installed controllers.
2. Provide a user interface to allow users without programming experience to remotely operate Cloudfridge.
3. Calibrate and validate error and data uncertainty relating to all sensors integrated into the Redshift board.
4. Identify the impacts of industrial-scale deployment on latency or other performance measures.
5. Complete project Objective 5.
6. Analyze the impact of ambient conditions on energy usage or assess control energy usage in the same ambient conditions as was done for Cloudfridge testing.
7. Develop and optimize control methodologies for maximum energy savings potential.
8. Complete a market analysis.

2.7.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research project is increased affordability of electricity in California. The researchers used a single installation to demonstrate energy savings potential of Cloudfridge. Baseline usage using the factory thermostat control showed energy consumption of approximately 80 kWh per week during the month of August. Using the Cloudfridge controller with a simple hysteresis control methodology, total energy consumption was 62.63 kWh per week during the test period in early November. Enhancing the control methodology to account for standard daily usage, peak activity time, and idle periods resulted in a total energy consumption of 31.70 kWh per week during the test period in mid-November. While the enhanced control methodology clearly showed improvements in energy usage between the two demonstration periods, the researchers did not address the impact of the significant ambient temperature difference between August, when the baseline was assessed, and November, when the demonstrations were performed. Without regard for additional energy loading due to increased ambient temperature, the energy usage was decreased by approximately 60 percent. The researchers estimated that Cloudfridge could deliver a 50 percent energy savings, totaling approximately $200 to $250 in annual savings per installation. The savings would be offset by the Cloudfridge annual subscription fee of approximately $20.

2.7.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have not yet surveyed potential customers or performed a market analysis. The primary market includes the food and hospitality industry. The technology may be used in new and retrofit refrigeration equipment installations.

Engineering/Technical

There are no obstacles to demonstrating the proposed technology. However further development of advanced control methods is needed for fully automated operations. The researchers anticipate that an additional $250,000 to $400,000 will be required for medium-scale testing.

Legal/Contractual

The researchers completed a provisional patent in November 2012, pending full application.

Environmental, Safety, Risk Assessments/Quality Plans

The researchers do not anticipate negative effects with regard to public safety or the environment.

Production Readiness/Commercialization

The researchers are currently developing a commercialization plan and do not intend to seek a commercialization partner.

2.8G Advanced Bioreactor Recycling System for Producing Energy and SNG (2011)

Awardee: University of California San Diego

Principal Investigator: Reinhard Seiser

2.8.1G Abstract

The energy content of municipal solid waste (MSW) is substantial and many technologies are available to convert this resource into fuels and chemicals. Conventional disposal of MSW by landfilling results in the conversion of some of the organic content to methane by anaerobic digestion. Advanced landfill bioreactors improve conventional anaerobic decomposition of the organic content from greater than 30 years to less than 15 years. However, much of the organic content is still present and may be further converted into fuels and chemicals through processes such as thermal gasification. This study focused on the excavation of partly degraded MSW from an advanced landfill bioreactor cell for the purpose of sorting/separating the organics for further processing to synthetic natural gas through thermal gasification. The researchers sorted the excavated waste and subjected it to size fractionation, a process in which a certain quantity of a mixture is divided into smaller quantities (fractions). That fine fraction contained less carbon than projected. The carbon content of the fine fraction could be increased by the removal of heavy inert material. However, the small amount of energy derived from the fine fraction requires the addition of large fraction material. The researchers found through analysis under gasification conditions that while the ash product had a suitable melting point (>1000° C), the ash contained relatively high levels of Cl and Hg that may require it to be handled as a hazardous waste. Finally, preliminary economic projections indicated that the gasification process was not competitive with the commercial process of creating natural gas from the landfill gas.

Keywords: Municipal solid waste, landfilling, waste mining, anaerobic bioreactor, waste gasification, landfill digestate

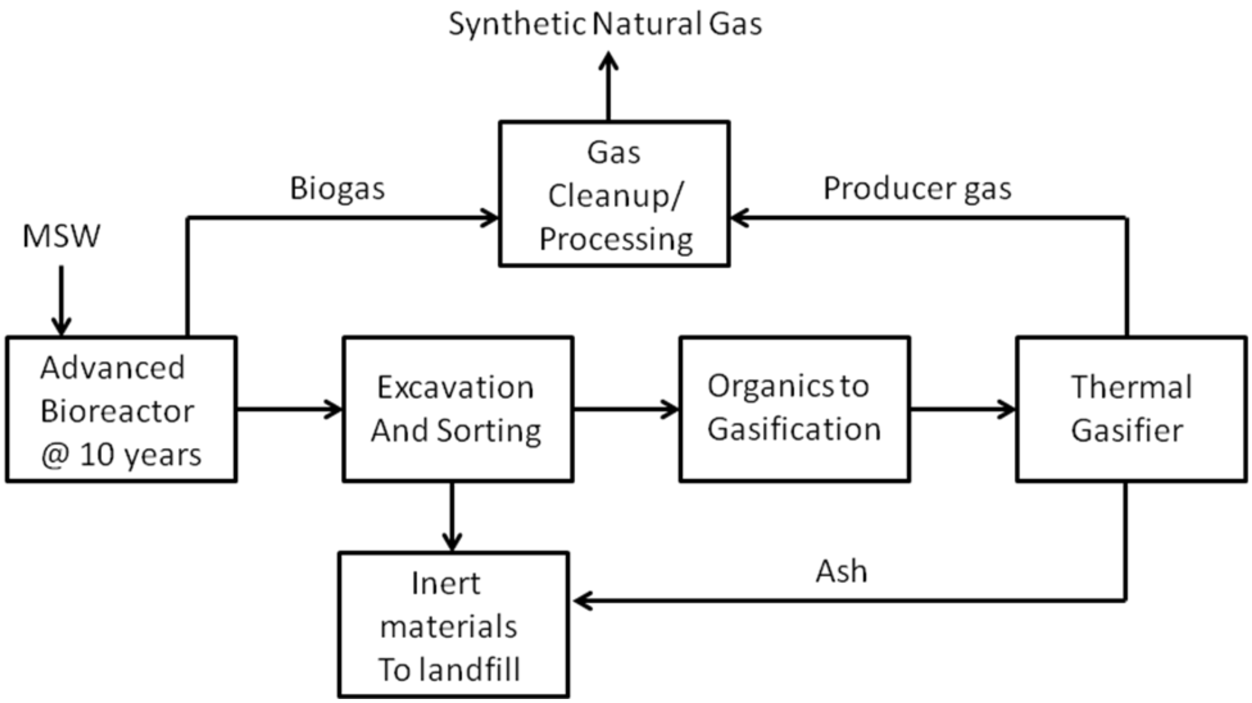
2.8.2G Introduction

Municipal solid waste (MSW) represents a continuous organic feedstock that may be considered for fuel and energy production. In 1997, the EPA estimated an annual production of 217 million tons. While a variety of technologies have been applied to convert MSW into fuels and chemicals, due to its heterogeneous nature, landfilling continues to be a low cost option for disposal. The relatively low cost of anaerobic landfilling MSW disposal and energy production has a substantial history. Medium-Btu biogas product is generally used on-site in internal combustion engine/cogeneration systems for the production of electricity and waste heat. Landfilling MSW causes anaerobic degradation due to microorganisms in the waste and the production of a biogas containing methane. However, the process is slow, generally requiring >30 years. The process is often incomplete due to a lack of optimized conditions, including moisture and microbial distribution. In addition, some organics such as plastics and lignin are not degraded by anaerobic microbes.

More recent advances in landfill design improve the rate of anaerobic decomposition of MSW through recirculation of leachate in the landfill cell, increasing both moisture and presumably the distribution of anaerobic microbes. These advanced bioreactor cells enhance the rate of anaerobic decomposition to 5—10 years at which time the biogas production rates decline precipitously. Owing to the incomplete decomposition, the landfill cell continues to contain a substantial fraction of organics that may be suitable for alternative conversion technologies. The ability to excavate an advanced bioreactor cell, separate organic from inorganic materials, and convert the organics using an advanced energy-generating technology such as gasification was the focus of this research project.

This project served to evaluate the residual material in an advanced bioreactor cell following a 10-year period of anaerobic decomposition. The researchers analyzed the material by size and evaluated it for composition. They subjected appropriate fractions of the waste to analysis for thermal gasification with a focus on the energy generated and the ash byproduct. The overall process is depicted in Figure 11.

Figure 11: Simplified Process Flow Diagram for the Advanced Landfill Bioreactor/Gasification Process



In this system, municipal solid waste is first subjected to anaerobic digestion in an advanced landfill cell. After 10 years, biogas production is diminished and the residual material in the landfill cell would be excavated, sorted, and the organic fraction subjected to thermal gasification. Ash and inert materials from sorting would be sent back to the landfill, while processed gas streams would be upgraded to synthetic natural gas.

2.8.3G Objectives

The goal of this project was to evaluate the possibility of recovering organic material from an advanced anaerobic landfill cell and using the material as feedstock for a thermal gasification process producing synthetic natural gas. The project focused on evaluating the contents of an anaerobic landfill cell following 10 years of operation after which the biogas production had decreased substantially. The researchers excavated landfill material and analyzed it for possible further processing by thermal gasification.

The researchers established the following project objectives:

1. Determine the chemical composition of an aerobic processed MSW sample for comparison purposes and develop a plan for collecting samples from two anaerobic advanced landfill cells. The aim is that one of the dried size fractions should contain >15 percent carbon.

2. Collect 15 samples from the two anaerobic advanced bioreactor cells and categorize them by size. The aim is to be able to screen 70 percent of the material through a one-inch screen.

3. Determine the proximate, elemental, and energy content of at least 10 samples. Report the composition and toxicity of the ash of at least 10 minerals. The aim is that one dried-size fraction will contain >20 percent carbon and less than 1,000 ppmw Cl and 0.1 ppmw Hg.

4. Determine the performance of selected samples in the gasification environment with measurement of gas composition and ash residue. The aim is to determine that the melting point of the residual ash is >1,000° C.

5. Estimate the total cost for the methane product per cubic foot and compare it with the market price for fossil fuel and renewable natural gas. The aim is that the methane should cost less than $15/MMBtu and less than $5/MMBtu accounting for landfill cost savings.

2.8.4G Outcomes

The research project was completed as designed and data analyzed in light of the objectives and aims. Project outcomes included the following:

1. The researchers completed analyses of the samples from the aerobic reactor and found that the manually sorted fraction, the fine fraction, and the moisture content were 28 percent, 32 percent, and 40 percent by weight, respectively. The combustibles in the fine fraction were 17.6w percent on a dry basis, and the researchers estimated the carbon content to be less than 10w percent. This data confirmed that the carbon content was less than the 15w percent goal.

2. The researchers collected samples from two anaerobic bioreactors and classified them by size and material. The manually sorted fraction and the fine fraction were about equal in amount. The manually sorted fraction contained mostly paper, wood, cardboard, film, and rigid plastics. The fine fraction was less than the 70w percent goal, and therefore a portion of the large size fraction should be considered for the gasification process. The researchers analyzed fine fractions from the anaerobic bioreactors for composition and energy content. They contained 16w percent combustibles (9w percent carbon). The researchers determined that a separation step for the fine fraction increased the carbon fraction to 38w percent, meeting the goal but increasing the processing costs.

3. The major inorganic elements were Si, Fe, Ca, Al, Na, Mg, K, and S. The content of Cl was 2,000 ppmw and that of Hg was 0.18 ppmw. This was considerably above the goals of 1,000 ppmw Cl and 0.1 ppmw Hg and would require additional processing to reduce or monitor levels before or after the gasification process. The energy content of the mined sample was 9 MJ/kg, in which the contribution of the manually sorted fraction was 8 MJ/kg and that of the fine fraction was 1 MJ/kg. The fine fraction was 90 percent

biocarbon-based, while the manually sorted fraction contained larger amounts of petroleum-based products.

4. The researchers analyzed several of the weight-separated samples of the fine fraction in a thermo-gravimetric analyzer . The samples showed a large amount of volatiles were released below 500° C. The ashes generated in both reducing and oxidizing atmospheres had melting points above 1,000° C.

5. The researchers estimated costs of a combined production of synthetic natural gas (SNG) to be $19.74/MMBtu. If only the landfill gas were converted to SNG, the researchers estimated the costs to be $7.66/MMBtu. These costs were considerably higher than target levels and could not justify implementation of the technology under the present economic setpoints.

2.8.5G Conclusions

To evaluate the suitability of the proposed concept and to perform preliminary economic projections, the researchers excavated representative samples from two anaerobic advanced bioreactor cells. They analyzed the samples for size and composition and did not meet preliminary goals. Additional separation of the fine fraction was necessary to achieve appropriate carbon content, resulting in increased processing costs. In addition, separated fine fractions were insufficient to provide enough energy for gasification and inclusion of the manually-sorted fraction would be needed to supplement the required carbon. The researchers performed experiments under gasification conditions on specific samples and identified an appropriate ash melting point, but elemental analysis identified Cl and Hg levels were outside the projected range and may require additional product-gas cleanup, further adding to the processing costs. Preliminary economic projections demonstrated high costs for the production of synthetic natural gas from gasification of residual organics derived from advanced landfill bioreactor cells.

In summary, the project data provided good information as to the content of advanced bioreactor landfill cells following >10 years of anaerobic decomposition. Data indicated that the recovered material from the advanced bioreactor cells was not as projected, requiring the further separation of the fine fraction (at additional cost) as well as needing large-size fraction material to be added to provide sufficient carbon content. While the Cl and Hg content was in a range to necessitate additional monitoring or processing, the researchers determined that the ash resulting from tests at gasification conditions had an appropriate melting point of >1,000° C. Economic projections indicated the cost to be prohibitive in comparison to current market costs for natural gas. Additional improvements in the economics of gasification and product-gas processing, landfill space recovery, and material recycling, and incentives for renewable energy production may eventually serve to improve the economics for the process to be competitive with natural gas.

2.8.6G Recommendations

This project served to enhance understanding of the composition of MSW waste following >10 years of anaerobic decomposition in an advanced bioreactor cell. Unfortunately, many of the projected parameters for the waste were not met and the process would require additional steps, increasing complexity and cost. Specific recommendations are related to enhancing the economics for the overall process as follows:

1. Determine if the ash generated from gasification of the waste contains sufficient leachable elements that would require its treatment as a Class II waste. Requiring Class II disposal of the ash would further increase the overall process costs.
2. Investigate the nature of the heavy fraction of the fine fraction and potential alternate uses, such as daily cover in the landfill.
3. Determine if the leachate from an advanced bioreactor cell could be used to separate the fine fraction, providing an alternative use for the leachate.
4. Evaluate further the nature and composition of the plastics in the large-size fraction and determine if recycling options are appropriate.
5. Generate additional samples from the advanced bioreactor cells through the use of core drilling at deeper levels to verify the consistency of the material.

2.8.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system.
- Increased public safety of the California energy system.
- Increased reliability of the California energy system.
- Increased affordability of energy in California.

The primary benefit to the ratepayer from this research are reduced environmental impacts of the California energy supply and distribution system. Alternative conversion of non-degraded organics from advanced bioreactor cells through gasification could provide additional renewable sources of synthetic natural gas. The location of large landfill facilities near highly populated cities could reduce transportation or the infrastructure required to utilize the additional synthetic natural gas. The application of this technology to municipal solid waste may enhance California's energy independence. By mining partly degraded material from landfills for use as feedstock for alternative renewable energy technologies, landfill space may be reclaimed. In addition, separated inert materials may be used for daily cover in landfill operation, reducing the need for alternative soil cover.

2.8.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

Due to the unfavorable projected economics for the process, the research team has not completed a comprehensive review of the market nor have they sought commercial sponsors to further develop the technology.

Engineering/Technical

It is unclear if the suggested improvements will improve the overall economics sufficiently to allow the cost of the synthetic natural gas to be competitive with natural gas. The researchers were evaluating the possibility of continuing this work at the end of this project.

Legal/Contractual

The research team has not reported any patent applications related to the process. Without an economic advantage, it is unlikely the research team will pursue a patent.

Environmental, Safety, Risk Assessments/Quality Plans

Environmental, safety, and risk assessments were not part of this project as the technology is still in the development stage. The gasification technology, together with product-gas handling, may be considered engineering intensive, and special considerations related to safety could be a major issue.

Production Readiness/Commercialization

Preliminary economic analysis demonstrated that the process was grossly expensive compared to the commercial cost for natural gas. Therefore, further development of the process is unlikely.

2.9G Achieving High Efficiencies in Natural Gas Internal Combustion Engines Through Solid State Microwave Assisted Spark Plugs

Awardee: University of California, Berkeley

Principal Investigator: Robert W. Dibble, Michael B. Frish

2.9.1G Abstract

Microwave enhanced ignition has the potential for significantly improving combustion stability at ultra-lean conditions, dramatically reducing the ignition energy needed to sustain combustion. The approach is to imbed a microwave antenna into a spark plug, which can create a microwave field in the spark plug gap within the combustion chamber. The microwave antenna is excited prior to and during the spark event and appears to create a much larger volume flame kernel with significantly less spark energy than conventional ignition systems. Researchers conducted experiments on a single cylinder Waukesha CFR spark ignition engine fueled with methane. The researchers determined the lean flammability limit of the engine by analyzing the coefficient of variation of the indicated mean effective pressure while the engine operated using a traditional spark plug and then on a solid state microwave-assisted spark plug. The lean flammability limit was extended by 10 percent when using the solid state microwave-assisted spark plug. The researchers also observed a reduction in pre-catalyst emissions. Nitrogen oxide was slightly reduced at the leanest operating conditions when compared to the leanest operating point for a standard spark plug. Carbon monoxide was reduced by 10 percent and unburned hydrocarbons were reduced by 30 percent at ultra-lean conditions. Numerical modeling supported these data. The results of this project suggest that microwave-assisted spark plugs can be an effective approach to reducing emissions and extending the operating range of natural gas spark ignition engines.

Keywords: Natural gas, spark plug, microwave, spark ignition, combustion, emissions

2.9.2G Introduction

Concern about greenhouse gases, air quality, and shortage of fossil fuels encourages the use of new technology and fuels that reduce emissions of combustion engines. Natural gas offers lower greenhouse gas emissions than other hydrocarbon fuels because of its high hydrogen-to-carbon ratio. It can also be combusted at high compression ratios without the risk of producing engine knock. Burning natural gas with air-fuel ratios larger than stoichiometric (lean conditions) in spark-ignited engines has the potential to produce lower emissions and higher thermal efficiencies than petroleum burning engines.

Lean internal combustion engines (those that operate with excess air) have favorable thermodynamics that yield high efficiency. However, conventional spark ignition systems do not reliably ignite the lean fuel-air mixture. The electrical discharge energy required to generate a flame kernel can be nearly two orders of magnitude higher for lean operation relative to stoichiometric fuel-air ratios (no excess air). Higher ignition energy rapidly ablates the spark plug ground electrode, resulting in both poor performance and durability.

Microwave-enhanced ignition has the potential for significantly enhancing combustion stability at ultra-lean conditions by dramatically reducing the ignition energy needed to sustain combustion. The approach is to imbed a microwave antenna into a spark plug, which can create a microwave field in the spark plug gap within the combustion chamber. The microwave antenna is excited prior to and during the spark event and appears to create a much larger volume flame kernel than conventional ignition systems.

The goal of this project was to prove the feasibility of this technology in a spark ignited engine fueled with natural gas. The researchers claimed that the benefits include an extension of the lean operating limit and a corresponding reduction in engine emissions.

There is a significant efficiency benefit to lean operation of internal combustion engines. The ability to run at lean mixtures allows a reduction of throttling losses at part load, thus mitigating a detrimental parasitic loss and increasing efficiency. Taking typical values for large engines, the effect of this efficiency increase loss is a 4.0 percent reduction in fuel consumption at idle and low loads, trailing off at higher loads. Applying this 4.0 percent efficiency to the amount of natural gas, biogas, and other forms of methane used in California during 2012 to generate electricity, the potential estimated gas savings is 45,000 MMBtu/year.

Previous studies conducted at UC Berkeley investigated the application of a first generation microwave spark plug (μWASP) to spark ignited engines fueled with gasoline[7] and methane.[8]

---

7 A. DeFilippo, S. Saxena, V. Rapp et al., "Extending the Lean Stability Limits of Gasoline Using a Microwave-Assisted Spark Plug," UC Berkeley, 2011. SAE Paper 2011-01-0663.

8 Vi H. Rapp, Anthony DeFilippo, Samveg Saxena, Jyh-Yuan Chen, Robert W. Dibble, Atsushi Nishiyama, Ahsa Moon, and Yuji Ikeda, "Extending Lean Operating Limit and Reducing Emissions of

This work was unable to investigate compression ratios above 10:1 because the microwave system could not deliver enough energy to influence the combustion characteristics at the higher pressures found at higher compression ratios. This is important since engine efficiency is directly correlated to the compression ratio. Since engines are being pushed to higher compression ratios for greater efficiency, the ability of microwave-assisted spark plugs to further extend the lean operating limit needed to be investigated. The researchers used a next-generation μWASP, also known as a solid state microwave-assisted spark plug (SSμWASP). Instead of a magnetron, which was used in previous models, the SSμWASP used solid state electronics commonly found in cellular phones, which generate a more powerful and easily controllable microwave pulse. Additionally, the solid state drivers can maintain a spark for durations of microseconds to one millisecond, essentially indefinitely relative to the timescale of a spark. This allows the application of more power over a shorter duration with better control of the timing.

The use of a μWASP has also been shown to decrease emission of total hydrocarbons (THC) and carbon monoxide (CO) by allowing for more complete combustion of the fuel-air mixture. It was previously shown that reductions of 10 percent for CO and THC are possible when using a μWASP compared to a standard spark plug. Emissions of the oxides of nitrogen can be reduced by extending the lean operating limits due to lower in-cylinder temperatures.

This project tested a novel microwave-assisted spark plug device that was different from those used in previous experiments.

2.9.3G Objectives

The goal of this project was to determine the feasibility of using a solid-state microwave spark plug in naturally aspirated, natural gas fueled IC engines through experiments and numerical modeling. The overall goal was to extend the lean operating limits and reduce regulated emissions. The researchers developed the following project objectives:

1. Demonstrate that the research engine is able to achieve stable operation (COV_{IMEP}<5 percent) with both a SSμWASP and a standard spark plug at typical operating conditions.
2. Demonstrate that the SSμWASP extends the lean limit by >20 percent.
3. Demonstrate reduction of CO and HC by >10 percent at equivalent ultra-lean operating conditions.
4. Demonstrate a reduction in NO_x emissions of >20 percent for a SSμWASP system at the leanest operating conditions when compared to the leanest operating point for a standard spark plug.

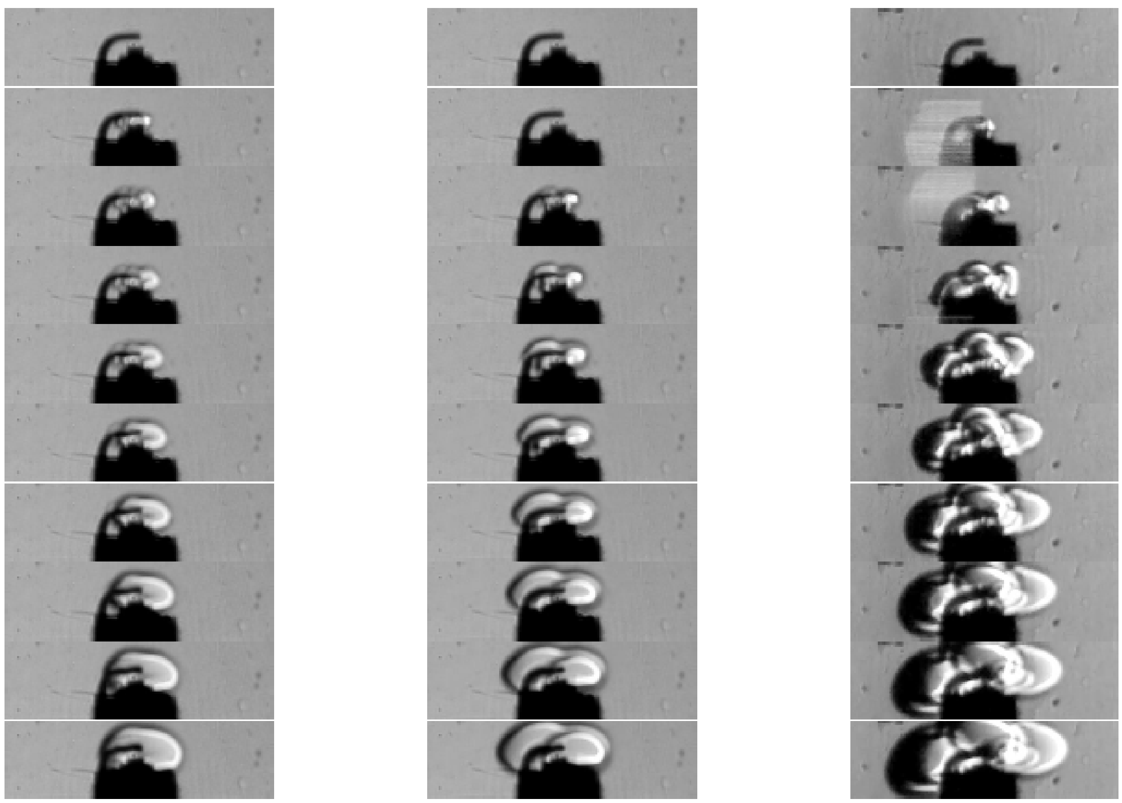
Methane Spark-Ignited Engines Using a Microwave-Assisted Spark Plug", *Journal of Combustion* (2012), Volume 2012, Article ID 927081.

5. Demonstrate that the numerical model is able to predict the lean operating limits and emissions characteristics within 10 percent.

2.9.4G Outcomes

1. Experiments conducted on the engine confirmed stable operation at stoichiometric and slightly lean conditions. Figure 12 shows the ignition and early flame development under three different conditions: no microwave, a 160 mJ (millijoule) microwave, and a 1,640 mJ microwave. The application of a microwave enhanced early flame development.

Figure 12: Depiction of Ignition and Early Flame Development Using Schilieren Images



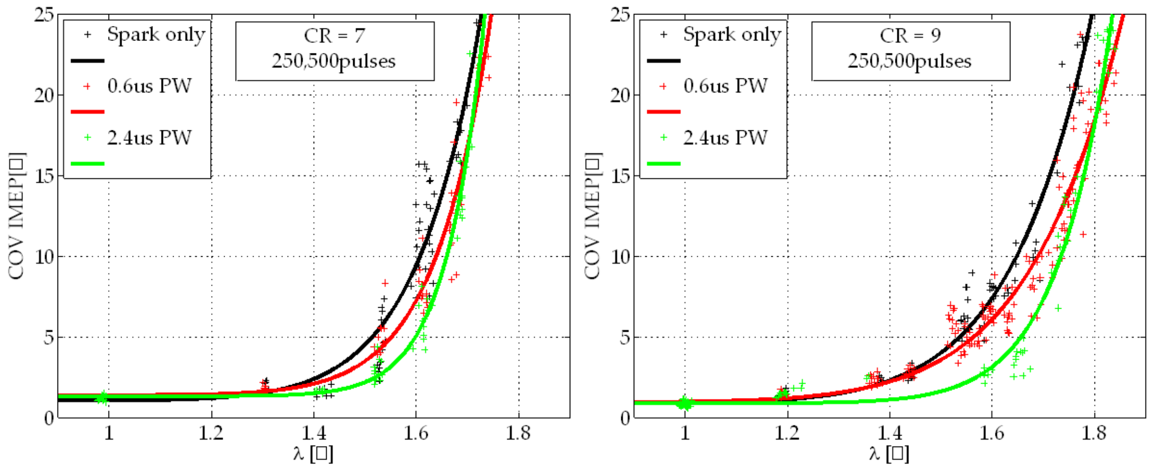
(A) (B) (C)

The frame rate is 1200 fps, resulting in a 0.83 ms time interval between two subsequent images. Image (A) is without microwave enhancement, image (B) is with little microwave enhancement [160 mJ], and image (C) is with 1,640 mJ of microwave energy.

2. The research team ran the engine at a variety of λ conditions using a standard spark plug and the SSμWASP device. These λ sweeps were conducted at different compression ratios, including 7, 9, and 12. Determination of the lean operating limit was done by interpreting the trend lines for the various microwave conditions (including no

microwave) seen in Figure 13. The lean limit was defined as the point where COV_{IMEP} exceeded 5 percent.

Figure 13: COV_{IMEP} vs λ Trend Lines for Compression Ratios (CR) of 7 and 9



The results indicated that even over a broad range of energies, the effect of the microwave was largely constant, although trailing off at very low numbers of pulses. Thus it seemed that microwave power was a more important factor than energy. Researchers also studied the timing of the microwave signal, varying from slightly pre-spark to half a millisecond afterwards.

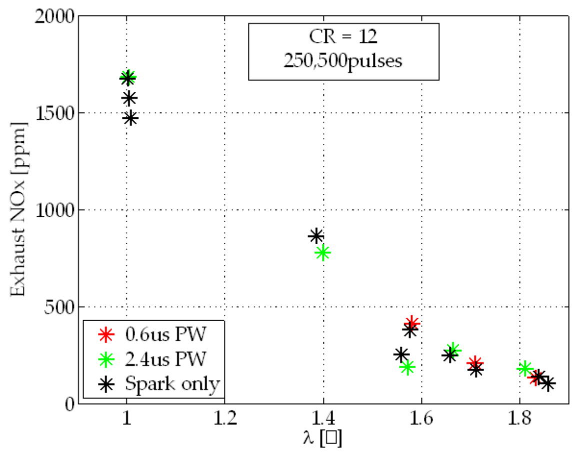
3. The researchers took emissions data for hydrocarbon (HC) and carbon monoxide (CO). CO emissions were reduced by 10 percent at ultra-lean operating conditions. This was based on RPM=900, CR=9, and the maximum microwave energy delivered. HC emissions were reduced by 30 percent at ultra-lean operating conditions based on the same parameters. Table 2 shows the values corresponding to the leanest operating point for each operating condition.

Table 2. HC and CO Emissions Reductions at Ultra Lean Conditions λ = 1.65, CR=9, 900 RPM, and Maximum Microwave Energy Delivered

Operating Condition	HC (ppm)	CO (ppm)
Spark Only	7100	710
SSμWASP	4900	565
	31% reduction	10.4% reduction

4. NO_x emissions were slightly reduced by 1.0 percent for a solid state microwave-assisted spark plug (SSμWASP) system at the leanest operating conditions when compared to the leanest operating point for a standard spark plug. This was based on RPM=900, CR=9, and the maximum microwave energy delivered. See Figure 14.

Figure 14: Exhaust NO_x Emissions vs λ at CR=7,9, and 12



5. While providing key data and results supporting the objective, this specific objective was not attained.

2.9.5G Conclusions

1. Researchers achieved stable operation at standard operating conditions on the engine using both a typical spark plug and a solid state microwave-assisted spark plug (SSμWASP) for a variety of compression ratios and RPM.

2. The researchers extended the lean limit of a spark ignition engine by using a SSμWASP system. Experimental results indicate a 10 percent extension of the lean limit, from λ= 1.5 with no microwave to λ= 1.65 with microwaves (2.4 μs pulse width, 500 pulses, 0.3 μs delay). This lean limit extension was slightly further than was previously achieved in the literature.

3. CO emissions decreased by 10 percent at ultra-lean operating conditions (λ= 1.65). HC emissions also decreased by 30 percent at ultra-lean operating conditions (λ= 1.65). These results were based on RPM=900, CR=9, and the maximum microwave energy (2.4 μs pulse width, 500 pulses, 0.3 μs delay) delivered.

4. Researchers found NO_x emissions reduced by 1.0 percent for a SSμWASP system at the leanest operating conditions (λ = 1.65) when compared to the leanest operating point for a standard spark plug (λ= 1.5). This objective was not achieved.

5. The researchers tested the present numerical model through ignition calculations with the goal of characterizing the factors governing microwave effectiveness. Modeled trends in reactivity enhancement against pressure and air-fuel ratios followed experimental observations of improved effectiveness at lower pressures and dilution of the reacting mixture with excess air. However the overall objective was not achieved. A predicted diminished ignition enhancement at low initial electron concentrations could

explain the experimental observation that microwave-assisted spark plug effectiveness diminishes when microwave input is delayed relative to dc spark breakdown.

6. The research team investigated different parameters for microwave delivery. These included pulse width, number of pulses, and delay based on spark triggering. The team found that the pulse width and number of pulses have a dramatic effect on engine performance, as they directly influence the amount of microwave energy delivered. The researchers found microwave delay had a negligible effect on engine performance.

7. The research team found that further device parameter optimization was needed to properly address the commercialization and marketing potential of the proposed technology. However, the experimental results pointed to the SSµWASP as a tool for increasing engine stability and efficiency while reducing key exhaust emissions.

2.9.6G Recommendations

While having some positive results, the research undertaken did not meet the proposed objectives, in particular those associated with lowering NO_x emissions by more than 20 percent. The Program Administrator recommends that the researchers:

- Investigate thoroughly microwave power delivery, including the trade-off in incident and reflected microwaves, to fully understand the optimal operating conditions of a solid state microwave-assisted spark plug.
- Create further data sets encompassing a greater range of compression ratios and RPM to create an engine operating map.
- Write an engineering product specification to begin the commercialization process.
- Define all the variables (pulse width, delay, and number of pulses) to maximize the potential of the product.
- Address packaging considerations in real-world applications.
- Add the capability for spatial modeling of flames subject to electromagnetic discharge. Challenges to implementing spatial simulation should include the numerical treatment of electron transport and quantitative modeling of charge near electrodes.
- Capture lean limit and emissions characteristics of a real engine using full CFD models and expanded mechanisms.

Demonstrating a significant reduction of NO_x emissions is critical to any further research.

2.9.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system.

- Increased public safety of the California energy system.
- Increased reliability of the California energy system.
- Increased affordability of energy in California.

The primary benefit of this research is the reduction of environmental impacts of the California energy supply and distribution system. The benefits emanate from reduced greenhouse gas emissions or reduced health and environmental impacts from NG use in electricity production and transportation.

This study demonstrated a lean stability limit extension for spark-ignition engines using natural gas. While the indicated specific fuel efficiency was not increased at the leanest operating point for each of the primary cases with and without a solid state microwave-assisted spark plug, there is a significant efficiency benefit to operating at ultra-lean conditions.

Researchers observed a reduction in pre-catalyst emissions through this process. Nitrogen oxide was slightly reduced at the leanest operating conditions when compared to the leanest operating point for a standard spark plug. Carbon monoxide was reduced by 10 percent and unburned hydrocarbons were reduced by 30 percent at ultra-lean conditions.

Unfortunately it is premature to estimate any statewide benefits from this technology.

2.9.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers had not surveyed potential customers for interest in this product by the end of this project nor had they performed a market analysis.

Engineering/Technical

Researchers estimated that $500,000 and two years would be required to complete engineering development. They did not have an engineering product requirements specification at the end of this project.

Legal/Contractual

No additional patent information or contracts have been received since the EISG grant.

Environmental, Safety, Risk Assessments/Quality Plans

These tests must be conducted by the device manufacturer.

Production Readiness/Commercialization

The product still requires a definitive research proof before commercialization can begin.

2.10G Electroporation of Algal Biomass to Enhance Methane Gas Production

Awardee: San Diego State University

Principal Investigator: Temesgen Garoma, A. Ege Engin

2.10.1G Abstract

This research project focused on the application of electroporation, a technique in which an electrical field is applied to cells in order to increase the permeability of the cell membrane, to pretreat algal biomass and thereby increase anaerobic biodegradation for the production of a fuel gas (methane) and the reduction in algal organic content.

The researchers designed, constructed, and tested a novel continuous flow, bench scale, electroporation cell and circuit board. The final design represented the result of several iterations in the power system and flow cell. While initially designed for a volume of 100 mL and a single pass flow, the flow cell was ultimately operated at a volume of 0.125 mL and with recirculation for optimum pretreatment.

The researchers examined a number of process parameters to optimize performance, including the treatment intensity of 28 kWh/m^3, a pH of 7.0, ionic strength (IS) of 30 mM, and algal process loading of 13.2 g/L. Optimum pretreatment resulted in a 109.2 ± 6.5 percent increase in methane generation from anaerobic digestion as compared to untreated algal biomass. Thus, under optimum conditions, fuel gas production was 342.8 ± 10.6 L of methane per kg of algal volatile solids added.

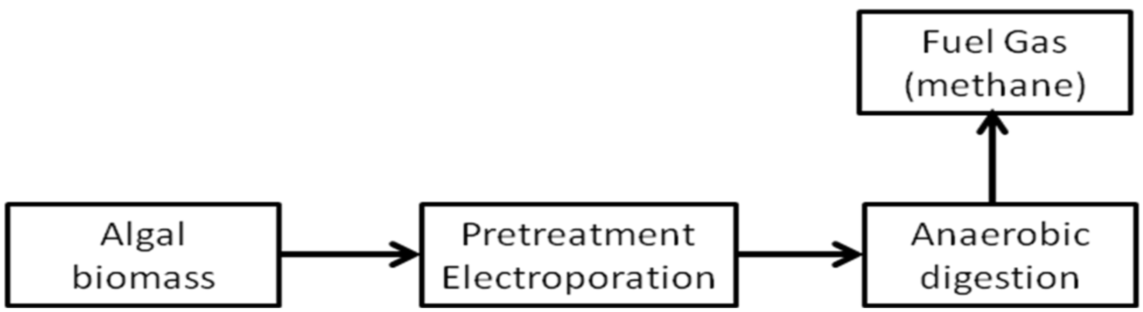
Keywords: Algal biomass, electroporation, anaerobic digestion, biomethane

2.10.2G Introduction

Algal biomass represents a renewable form of organic biomass for conversion to fuels and chemicals. Algae have also been proposed to provide a sink for carbon dioxide produced from other industrial processes. As such, algae can provide an environmental benefit as well as carbon offset value.

The amount of organic matter in algal biomass is substantial. Previous studies have focused on the conversion of algal biomass to fuel and chemicals through a variety of thermal, chemical, and biological processes. This research project focused on the application of anaerobic digestion for conversion of algal biomass to a fuel gas containing methane. However, anaerobic conversion of algal biomass is low, owing to the protective nature of the cell wall/membrane of algal cells. Pretreatment of algal biomass has the promise of releasing entrained organics to improve anaerobic conversion to methane. The overall process is depicted in Figure 15.

Figure 15: Proposed Process to Pretreat Algal Biomass by Electroporation Prior to Anaerobic Digestion



Electroporation has been used as a molecular biology technique in which an electrical field is applied to cells to increase the permeability of the cell membrane, allowing chemicals, drugs, or DNA to be introduced into the cell. At increased energy levels a substantial disruption of the cell wall/membrane could allow intracellular organics to be released. The release of volatile organics may then be converted more efficiently by the anaerobic consortium to the end product, methane. An important aspect of the technology development is to ensure that the amount of energy required for pretreatment is less than the energy in the fuel gas product derived from the enhanced anaerobic bioconversion.

This research project addressed major issues related to energy and the environment in California as follows:

1. The production and conversion of algal biomass to fuel gas in California directly addresses the State's mandate to generate energy from renewable resources. From carbon dioxide and sunlight, algae can produce organic biomass which may be processed in a variety of conversion processes, such as anaerobic digestion, to fuels and chemicals. This research project focused on improving this process through a novel pretreatment technology employing electroporation.

2. As algae may be used to remove carbon dioxide from industrial process gases, the opportunity for conversion of algal biomass to energy could provide for relatively low cost fuel for direct conversion to electricity or for upgrading to pipeline-quality natural gas. Depending on the scale and efficiency of the algal biomass conversion system, lower cost energy may be derived from the process providing a more stable and sustainable energy source and reducing costs for California ratepayers.
3. The application of electroporation to pretreat algal biomass for enhanced anaerobic bioconversion is novel. Previous application of electroporation has been to provide a mode to allow entry of biomolecules into cells. The researchers instead sought to disrupt algal biomass extensively, allowing organics to be released from cells and thereby providing availability for anaerobic bioconversion to methane.

Commercial production of methane from algal biomass for use in transportation fuels or electricity generation is currently an expanding market. The application of algal biomass production provides a renewable and sustainable method for carbon dioxide sequestration. Its conversion to methane fuel through anaerobic bioconversion represents a relatively low-risk process. The development of a safe and effective pretreatment technology is the only major impediment to the development of this renewable energy source.

2.10.3G Objectives

The goal of this project was to determine the feasibility of employing electroporation as a pretreatment to enhance the anaerobic bioconversion of algal biomass to fuel gas containing methane. The researchers established the following project objectives:

1. Design and build a continuous flow electroporation system with a chamber volume of 100 mL.
2. Establish values for process parameters, including applied pulse voltage, pulse width, pulse frequency, electrical field strength, and treatment times that result in methane gas yield by anaerobic digestion of 0.5 L/gVS.
3. Establish culture conditions including algal biomass concentration, ionic strength, and pH that lead to an increase in methane gas yield from values reported in the literature to an enhanced yield of 0.5 L/gVS.
4. Demonstrate an increase in methane gas yield from the current literature reported values of 0.17—0.34 L/gVS to an improved yield of 0.5 L/gVS.
5. Determine the specific energy use for electroporation in joules/mL at optimum pretreatment conditions with comparison to the methane gas yield of 0.5 L/gVS.

2.10.4G Outcomes

The research project resulted in a number of successful outcomes including the following:

1. The research team designed and constructed a bench-scale, continuous flow electroporation system for pretreating algal biomass. The team reconfigured the reaction

cell to a volume of 0.125 mL that represented 1/800 of the original working volume of 100 mL. The limitation to the reaction cell volume was due to the required optimum applied voltage necessary (i.e., 2.4 kV) that was deemed to be dangerous at higher voltage.

2. Pretreatment experiments identified an optimum pulse width of 10 microseconds. In addition, the researchers determined the optimum treatment intensity as 28 kWh/m^3. This treatment intensity resulted in an increase in the soluble chemical oxygen demand released from the algal biomass of 832 ± 29 percent.

3. The researchers evaluated additional algal biomass parameters, including pH, ionic strength, and biomass concentration for optimum pretreatment effectiveness. They found a pH of 7.0, ionic strength of 30 mM, and an algal biomass concentration of 13.2 g/L to be optimum for the configuration and operation of the pretreatment cell in its current design. Optimizing these parameters led to a change in soluble carbon oxygen demand of 177—223 mg/g during electroporation.

4. While optimum electroporation pretreatment of the algal biomass demonstrated a greater than 800 percent increase in the soluble carbon released, and presumably available for anaerobic bioconversion, actual product methane was little more than two times that for untreated algal biomass. Therefore the target yield of 0.5 liters of methane per gram of volatile solids was not obtained, and the maximum methane yield was only 0.342 liters per gram of volatile solids.

5. The specific energy use for optimum electroporation pretreatment of algal biomass was 35.0 kWh/m^3 equivalent to 126 joules/mL of algal biomass treated. The researchers estimated that 41 percent of this energy use was lost to heat. Regardless, due to the low level of anaerobic bioconversion of the soluble organics released as a result of algal biomass pretreatment, the energy content of the increased methane product was less than the energy used in pretreatment.

2.10.5G Conclusions

The researchers focused on an aggressive application of electroporation in which algal cells are completely disrupted allowing for the release of intracellular organics without the ability of treated cells to recover and restore the cell wall/membrane. The treatment therefore needed to be substantially greater than for conventional electroporation systems used in fields such as molecular biology.

One conclusion suggests engineering of the electroporation treatment cell and electronics requires additional work since the optimum release of soluble organics required the treatment cell to be reduced by greater than 800 percent and to be operated in a recirculation mode. While it is clear that this technology is in the development stage and operated at bench scale, a flow cell of 0.125 mL is clearly a major limitation at this point.

The development of the electronic components for electroporation pretreatment was a major undertaking considering the application of substantial destruction of the algal biomass necessary for release of soluble organic carbon. The researchers were able to identify the optimum parameters including pulse width and treatment intensity which resulted in a substantial increase in release of soluble organic carbon from algal cells (greater than 800 percent). However this was accomplished with a very small treatment cell and employed recirculation of the algae through the treatment cell. Therefore, significant alterations in the circuit board will be required when the treatment cell is redesigned for a larger volume and single pass of biomass through the cell. Of great importance was the identification of the process parameters which enhanced the treatment effectiveness, including pH, ionic strength, and biomass concentration.

The research team demonstrated the capability to bring about substantial destruction of the algal biomass and release of soluble organic carbon. However, the conversion of the soluble organic carbon in the anaerobic bioconversion process was disappointing, and the optimum methane product generation was 0.343 liters per gram of volatile solids, considerably below the target of 0.5.

A review of the energy costs for pretreatment with the additional energy produced in the anaerobic bioconversion showed the process has a negative energy balance at the optimum treatment conditions. However, the researchers presented reasons to believe that this can be easily changed.

While the proposed electroporation pretreatment technology for algal biomass to methane holds significant promise to improve the economics for commercial-scale production, the technology is at an early stage and will not transition to commercial development in the near future without substantial funding assistance.

2.10.6G Recommendations

This research project was developmental in nature and thereby requires additional efforts to be successful. The following efforts will lead to a better understanding of the process and the potential for use in a commercial application. The Program Administrator recommends the following activities be part of any additional research effort:

1. Redesign the treatment cell and electronics to allow for high volumes of algal biomass to be treated, single pass operation, reduced joule heating, selection of durable materials for the treatment cell construction, and enhanced safety in the power system.
2. Develop understanding of the anaerobic bioconversion process, including optimizing the microbial populations for efficient conversion of the algal-derived organics to the end product fuel gas.
3. Develop a treatment cell with greater volume and appropriate materials for durability. The treatment cell should also allow single pass treatment of algal biomass with optimum release of soluble organics.
4. Develop a circuit board package with greater output and improved safety.
5. Perform a rigorous process economic analysis for full-scale application.

6. Demonstrate pilot-scale testing to confirm process conversion rates and yields.

2.10.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system.
- Increased public safety of the California energy system.
- Increased reliability of the California energy system.
- Increased affordability of energy in California.

The major benefit derived from this project is the increased reliability of the California energy system. Development of more sustainable methods for producing organic biomass and conversion to fuel gas could reduce reliance on natural gas for the production of electricity. Fuel gas derived from this process may be upgraded and used as transportation fuel, thereby reducing emissions.

Since the proposed technology is still at a relatively early stage of development, the researchers have not achieved the goal of producing methane efficiently from algal biomass. The quantitative benefit to California is zero at this stage.

The researchers project that if the technology is successful, commercial application could result in 9670 GWh of renewable energy per year.

2.10.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

Currently, the researchers are at a very early stage in the process development and have not sought marketing contacts for the process.

Engineering/Technical

The researchers stated that they can complete demonstration in three to five years with relatively low levels of funding. Due to the early stage of development, this funding will likely not come from industrial sources but rather must be supplied by government programs that foster this type of early stage development.

Legal/Contractual

By the end of this project the research team had not applied for nor secured patents on the technology. This may hinder the ability to gain commercial support for developing scale-up projects. The researchers published an article (DOI: 10.1016/j.biortech.2014.07.001) based on the results from this project. They claimed they did not disclose any data that would limit their ability to seek patent protection.

Environmental, Safety, Risk Assessments/Quality Plans

Environmental, safety, and risk assessments were not part of this project as the technology is still in the developmental stage. However, the research team limited the technology development relative to the output of 2.4 kV for safety concerns. The safety risk in the development of the electronics component of the electroporation system was therefore a major limitation to the success of the project.

Production Readiness/Commercialization

The electroporation technology still requires development at laboratory-scale. Following these improvements the process will require scale-up demonstrations to be ready for commercial development.

2.11G Low Cost Glazed Polymer Solar Water Heater

Awardee: Rhotech Solar, LLC

Principal Investigator: Richard Rhodes

2.11.1G Abstract

This research demonstrated the feasibility of adding a polymer glazing layer to improve thermal efficiency of an existing low cost polymer solar collector and heat exchanger system. Efficiency gains with glazing exceeded 40 percent and peak temperatures surpassed 70° C in a mild climate. In hotter climates, the collector with glazing was calculated to reach stagnation temperatures as high as 87° C. Such temperatures would exceed the maximum use temperature of the polymer that would damage the materials employed. Thus higher temperatures with the glazing demonstrated the need for a stagnation control means. Accordingly, researchers in this project developed and tested various stagnation control methods. They found that a solar electric pumped water-to-air heat exchanger provided adequate heat rejection. The researchers concluded that the system with glazing had the potential to save energy when installed as a preheater in line with a conventional natural gas water heater. Under those conditions, the glazing's 40 percent boost in collector efficiency directly translated into a reduction in natural gas usage. The researchers estimated the cost of producing and installing a complete solar collector system (including glazing and stagnation control) at under $600.

Keywords: Solar water heater, solar pre-heater, polymer glazing, polymer heat exchanger, stagnation limiting

2.11.2G Introduction

The primary energy sources for California are electricity, natural gas, and crude oil. These three sources use combinations of fossil fuels and are major emitters of greenhouse gases. In particular, residential and commercial natural gas end-users were responsible for the consumption of 686 billion cubic feet per year (bcf/y) of natural gas out of a total State consumption of 2,313 bcf/y in 2012.[9] The California Air Resources Board calculated natural gas consumption by residential and commercial end-users caused the emission of 37 million metric tons (MMT) of GHG in 2012.[10] Commercial natural gas uses about one half of residential.[3] In 2012, space heating accounted for 46 percent of residential natural gas consumption, and residential water heating accounted for another 42 .[11] Assuming the same natural gas fraction for the commercial water heating sector, residential and commercial water heating are estimated to account for about 10 MMT and 5 MMT of GHG emissions, respectively. Because of the large amount of natural gas consumed by water heating, there has been great interest in solar thermal pre-heating to reduce the combustion of natural gas. However, to be effective in the marketplace, a solar pre-heater would have to be inexpensive with a short payback time. Existing pre-heaters often use expensive materials including copper and glass. These materials are rigid and cannot be folded to reduce shipping costs. Accordingly, there is interest in less expensive preheaters constructed of inexpensive polymers that are flexible. However, to be of use, polymer preheaters must be efficient and reliable. Unfortunately, the polymers of interest are sensitive to temperatures of about 80° C for long-term use and must therefore be protected from high stagnation temperatures. What is desired is an efficient, low cost, and long-lived polymer preheater with built-in protection to dissipate heat during high stagnation temperature conditions.

If such a low cost, long-lived preheater could be developed, the payoffs could be large. While solar water heating has been carried out for a long time, significant benefits will be realized only if market penetration is high.[12] The price scale is roughly established by the cost of existing residential gas water heaters on the order of $500—$1,000. The United States Office of Energy Efficiency & Renewable Energy calculator, with default settings for a natural gas powered water heater with a daily hot water consumption of 64 gal., predicts a yearly cost of operation of $146 and a lifetime cost of operation of $1,514.[13] Assuming an approximate 50 percent replacement of natural gas consumption for a 30—40 gal. tank water heater system averaged over daytime and nighttime use and the estimated 10 MMT of GHG emitted by residential water heating, a reduction in GHG emissions in the order of 5 MMT at high market penetration appears

---

9 http://energyalmanac.ca.gov/naturalgas/overview.html

10 http://www.arb.ca.gov/cc/inventory/data/tables/ghg_inventory_scopingplan_00-12_2014-03-24.pdf

11 http://energyalmanac.ca.gov/naturalgas/overview.html

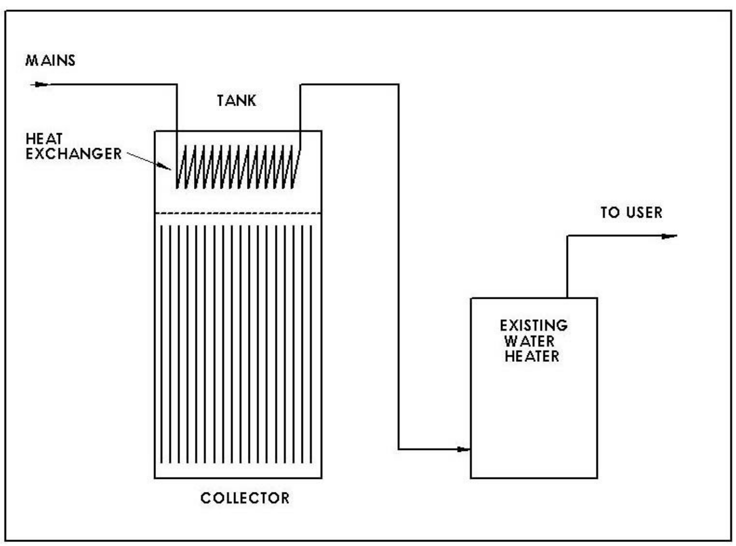
12 http://en.wikipedia.org/wiki/Solar_water_heating

13 http://energy.gov/eere/femp/energy-cost-calculator-electric-and-gas-water-heaters-0#output

possible. For high market penetration a preheater should have an installed cost of less than $1,000.

The advancement proposed in this project was the addition of a transparent polymer glazing material to an existing unglazed polymer solar preheater. Figure 16 shows a schematic of a solar preheater system added to an existing water heater. At the start of this project the researchers had already developed a polymer-based collector with an integral hot water accumulator tank and heat exchanger. The collector was unglazed so it had relatively high heat loss to the ambient air by conduction and radiation. The stagnation temperature was low when no water was drawn from the mains. The researchers proposed to increase the efficiency of the added solar fraction by 20 percent by suspending a polymer sheet glazing over the collector. The sheet was transparent in the visible spectrum and relatively opaque in the infrared. However, the glazing was expected to raise the stagnation temperature in the collector water tank to values too high for the polymer heat exchanger and other components. Thus, the challenge was to develop a means of lowering the stagnation temperature by dissipating heat to the ambient air under stagnation conditions. Another challenge was to securely mount the glazing suspended over the collector-absorbing surface and still be able to withstand wind buffeting of the film glazing.

Figure 16: Schematic of Solar Preheater Attached to Existing Water Heater



The main objective was to add an inexpensive spectrally selective polymer glazing sheet over the collector.

2.11.3G Objectives

The goal of this project was to determine the feasibility of adding a glazing layer to improve thermal performance and develop a means of limiting the stagnation temperature of a newly developed low-cost thin-film polymer solar water heater, thereby decreasing consumption of natural gas for heating domestic water by at least 70 percent. The researchers established the following project objectives:

1. Build three prototypes with glazing and stagnation temperature control. Install data acquisition for monitoring. The first prototype is to be unglazed. The second prototype is to have glazing. The third prototype is to have glazing and a heat rejection system.
2. Test prototype glazing designs side-by-side. Measure the stagnation temperatures with thermal probes. Calculate the worst-case maximum stagnation temperatures. Verify that the glazing increases the measured stagnation temperature to above 60° C. Demonstrate that the calculated worst-case stagnation is above 80° C.
3. Evaluate and test side-by-side stagnation temperature limiting with the glazing configuration and heat rejection system. Verify that the measured and calculated worst-case stagnation temperature is less than 80° C with a heat rejection system.
4. Verify thermal performance improvement. Demonstrate greater than 20 percent improvement in heat absorption from 8,200 Btu per day for the unglazed system to at least 9,840 Btu for glazed systems.
5. Complete product design and production equipment concepts. Verify installed cost estimates less than $750 per system at production volumes greater than 10,000 per year.

2.11.4G Outcomes

1. The researchers assembled an outdoor inclined test rack to simulate roof mounting of collectors. Data acquisition hardware supplied by the National Renewable Energy Laboratory monitored performance using temperature sensors, a wind meter, and a solar radiation sensor. The researchers constructed and tested three prototype test units. The first was unglazed, the second had glazing, and the third had glazing and a means for heat rejection (stagnation control).
2. The researchers tested two thicknesses of polyester terephthalate glazing, one 92 gauge UV stabilized film and the other a 200 gauge unstabilized film. The 92 ga. film was 1 mil thick and the 200 ga. was 2 mils thick. During one set of tests the researchers measured a stagnation temperature of 65° C in the glazed collector, more than 11° C hotter than the adjacent unglazed collector. In another set of tests, a glazed collector reached 70° C in ambient air of 27° C with wind gusts to 8 mph. In a hotter environment the collector temperature could reach a calculated 87° C, exceeding the safe use temperature. Significantly, however, both the 1 mil and 2 mils glazing films failed during windy conditions.
3. Attempts to limit peak collector temperatures to less than 80° C with passive cooling yielded only a 6° C cooling effect, insufficient for hot climates. The researchers developed an active cooling method with a water-to-air heat exchanger and solar-powered water pump, which reduced water temperature by 14° C. They calculated this

cooling effect could reduce the water stagnation temperature to 79° C in an assumed worst case 43° C ambient air, meeting the less than 80° C criterion.

4. In side-by-side testing, glazing increased the energy collected from 7,500 BTU to 10,500 Btu, an increase of 40 percent in performance.

5. The researchers estimated cost for an installed residential glazed preheater system with heat rejection would be $532 in quantities of 1,000. Capital cost for setting up production facilities for 60,000 to 120,000 units per year was estimated at $670,000.

2.11.5G Conclusions

1. The researchers met these goals.

2. The researchers met these goals.

3. The researchers met this goal with an active cooling system. The solar electric active pump added no parasitic losses.

4. The researchers surpassed this goal.

5. While the researchers met this goal on paper, the numbers must be carefully reviewed. Their projected installed cost of a solar preheater system for domestic hot water was dramatically lower than currently available installed systems. Since cost is a key factor in market acceptance, the cost calculation must be carefully reviewed and tested in different market areas of California. The Florida Solar Energy Center estimates the cost to install a solar water heating system to be between $3,500 and $5,500 with current technology.

Overall the researchers proved feasibility of added glazing, thus improving collector efficiency. They demonstrated a low cost stagnation temperature limiting method. It is disturbing, however, that both glazing films failed in windy and inclement weather.

2.11.6G Recommendations

The next work to be conducted appears to be primarily at the level of product development rather than research. The Program Administrator recommends that the researchers:

- Find a means to demonstrate secure glazing film integrity under windy conditions and during inclement weather.

- Conduct a wide review of existing California building codes to make sure there are no surprises uncovered when the researchers come to market the device. Determine if any code requirements could increase the installed cost.

- Conduct detail manufacturing cost analysis including overhead, insurance, warranty costs, sales and marketing, and profit.

- Estimate the average installation cost on an existing California house using local labor rates. Include the cost of any additional platforms, tanks, plumbing, valves, and other balance of materials needed for the installation.
- Develop cost models for the consumer. Determine the payback time for various delivered natural gas prices.
- Conduct market analysis once the cost analyses have been completed. Determine the potential market size at that price point.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.11.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system.
- Increased public safety of the California energy system.
- Increased reliability of the California energy system.
- Increased affordability of energy in California.

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system. If such a low cost, long-lived preheater could be developed, the payoffs could be large. While solar water heating has been marketed for a long time, its benefits will only be realized if market penetration is high. The price scale is roughly established by the cost of existing residential gas water heaters on the order of $500—$1,000. For a natural gas water heater with a daily hot water consumption of 64 gallons, the United States Office of Energy Efficiency & Renewable Energy calculator with default settings predicts a yearly cost of operation of $146 and a lifetime cost of operation of $1,514. To obtain high market penetration, a preheater system should have an installed cost of less than $1,000. Even with a 40 percent fuel savings, the average consumer would not recover the initial capital cost for over 17 years. If natural gas prices remain low, the cost recovery time could be extended. Market penetration could be low with these lengthy payback periods. System costs of higher than $1,000 could lead to an insignificant market size.

Assuming an approximate 50 percent replacement of natural gas consumption for a 30—40 gal. tank water heater, a reduction in GHG emission in the order of 5 MMT at high market penetration appears possible. Market penetration is the key factor in assessing GHG benefits to California.

2.11.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers had not performed a market analysis by the completion of this project. They plan to seek partners to take the product to market.

Engineering/Technical

The researchers plan to continue the development of this concept. They estimate they will need about $100,000 and one year of time to complete development.

Legal/Contractual

The researchers had not performed a patent search, but they had applied for patents by the completion of this project.

Environmental, Safety, Risk Assessments/ Quality Plans

Potential building code barriers in some locations may be flammability and structural resistance to wind loading. If brine or glycol is needed, toxicity may be a problem.

Production Readiness/Commercialization

After the development is complete, the researchers plan to partner with an industrial company to commercialize.

2.12G Improved Energy Efficiency of Natural Gas/Producer Gas Fuel Mixtures

Awardee: University of California, San Diego

Principal Investigator: Kal Seshadri

2.12.1G Abstract

Researchers in this project developed an improved technique, using a neural network, to estimate the methane number for different mixtures of gaseous compounds in producer gas. Producer gas can be made from the gasification of woody biomass and other resources. The use of biomass-derived producer gas to complement natural gas can increase the use of renewables in power generation using reciprocating engines. Uncertainty in the specification of the methane number for the producer gas/natural gas combination results in lower energy efficiency. The lowered efficiency is due to a necessary lower engine compression ratio to prevent engine knock.

Researchers completed single-cylinder variable compression ratio engine experiments on a range of simulated producer gas (H_2, CO, CO_2, CH_4, and C_2H_4) mixtures to generate a database for a neural network model for methane number prediction. The neural network model provided improved precision in methane number prediction, 2.3 percent, compared to the standard AVL[14] model that has a large uncertainty of 36 percent. This improved precision allows a higher compression ratio without knocking and thus higher engine efficiency. With producer/natural gas mixtures, the expected engine efficiency increases 22 percent with a 22 percent decrease in the levelized cost of electricity for a typical 1—2 megawatt system. Commercialization of the neural network model for methane number prediction requires the development of appropriate user software and a data base for commercial internal combustion engines.

Keywords: Neural network, internal combustion engine, methane number, producer gas, natural gas, energy efficiency

14 In computer science, an AVL tree (Georgy Adelson-Velsky and Landis' tree, named after the inventors) is a self-balancing binary search tree.

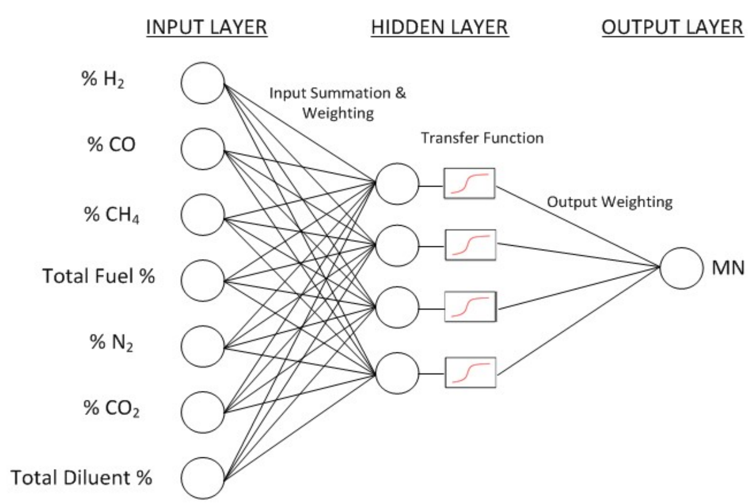
2.12.2G Introduction

Encouraging the development of renewable energy resources remains a high priority of California's energy policy. Part of the policy's rationale is the possibility of many renewable energy sources reducing the carbon intensity of electricity production. The carbon intensity of natural gas power generation, currently the single largest fuel used to generate California's electricity, can be reduced by using renewable producer gas from some biomass resources.

Limitations on the use of producer gas (a combination of H_2, CH_4, CO, C_2H_4 and CO_2) include the difficulty of predicting the real world performance of engines using fuel mixtures that have a wide variation in gas composition. Gaseous fuels can be characterized by a methane number (MN) which, like the octane or cetane number for liquid fuels, can be used to specify the maximum compression ratio of an internal combustion engine. Analysis of existing data has shown the standard method developed by AVL for predicting the methane number produces significant uncertainty.

In this project, researchers developed and evaluated an improved method for predicting the methane number maximum compression ratio and engine efficiency. They generated a data base of engine knock characteristics versus methane (natural gas)/producer gas composition to develop a neural network model with one hidden layer. The data base was created using commercial software to verify the predictions. The neural networks logic flow is shown in Figure 17.

Figure 17: Neural Network Schematic



2.12.3G Objectives

The goal of this project was to determine the feasibility of predicting the methane number of methane/producer gas fuel mixtures using a neural network model to improve energy efficiency in power production from internal combustion engines. The researchers established the following project objectives:

1. Identify at least three categories of existing producer gas compositions/methane number data with low, medium, and high hydrogen content for use as a data base for the development of the neural network model.
2. Define category levels for hydrogen content and design systematic variation of balance gas composition.
3. Improve the engine controls program to reduce the RMS error in operation to less than 3.0 percent, enhancing data precision.
4. Establish knock limits associated with the three methane/producer gas fuel mixtures to a precision of 3.0 percent.
5. Improve the accuracy of the prediction of methane/producer gas methane number to better than 10 percent.
6. Improve energy efficiency prediction for the use of methane/producer gas mixtures by at least 5.0 percent over the baseline prediction from the current standard AVL model.

2.12.4G Outcomes

1. The researchers established three hydrogen content levels to use in characterizing the relative importance of hydrogen content on the methane number of 52 different gas mixtures. The researchers grouped the blends in terms of low (< 25 percent), medium (> 25 percent and < 40 percent), and high (> 40 percent) hydrogen. They developed a neural network model for each category of hydrogen content based upon experimental results from a prior study.
2. The researchers established a test plan matrix for physical engine experiments to obtain a methane number measurement for each of 35 blends.
3. The researchers developed a modified fuel blending system to accelerate the mixing of target blends and improved the precision of blend constituency. The test engine had a variable compression ratio of between 4:1 and 18:1. The researchers measured the onset of knock and the actual methane number for each of the blends.
4. The researchers collected data on the highest compression ratio before the onset of engine knock with an average error of 1.2 percent. The researchers used 85 percent of that data to create a learning base for the neural network. The data included 52 gas blends with variations in the H_2/CH_4 ratio with and without ethylene, water gas shift, CH_4 variation due to biomass type, ethylene, H_2/CO ratio, and variation in the CO_2 level. The researchers trained the neural network with th 85 percent of the data.
5. The researchers used the trained neural network model to predict the methane number and compared the calculated number with the measured methane number from the experiments. The average error of the neural network model was 2.3 percent compared with 36 percent for the AVL model using 15 percent of the data base for verification.

6. The researchers measured an average 35 percent error in internal combustion engine efficiency predicted with the AVL model. The researchers estimated a neural network average error of 4.0 percent error in the predicted efficiency.

2.12.5G Conclusions

1. The gas compositions were categorized by hydrogen content, a driver of the methane number. The researchers completed this objective.
2. The researchers developed a test matrix for neural network model training that contained hydrogen variation by three different methods and systematic variations of other producer gas constituents. The resulting matrix contained seven different variations that mimicked actual variations that could occur in producer gas due to various woody biomass gasifier conditions.
3. The researchers measured knock limits to a precision of 3.0 percent. They designed a new flow controls system to improve the producer gas blending system accuracy.
4. The researchers estimated knock limits associated with the methane/producer gas fuel mixtures to a precision of 3.0 percent and an average error of 1.2 percent. They executed the test matrix twice, resulting in 104 independent methane number measurements for 52 producer gas blends. Thus they created a database suitable for training and testing the neural network model. The researchers completed this objective.
5. The prediction of a methane/producer gas methane number can be made with the neural network model to an average error of 2.3 percent compared with 36 percent for the AVL model. The researchers completed this objective.
6. Predicting energy efficiency in the use of methane/producer gas mixtures can be accurate to +/- 4.0 percent using the neural network model. The researchers completed this objective.

The researchers demonstrated feasibility of using neural network modeling to estimate the methane number of producer gas/natural gas mixtures based on constituent makeup and predict engine knock limit and efficiency in internal combustion engines. The neural network model has improved accuracy and precision compared to the traditional AVL approach.

2.12.6G Recommendations

The Program Administrator recommends that the researchers:

1. Expand the methane number matrix to further improve accuracy of the model under broader conditions of producer gas makeup.
2. Partner with a software company and/or engine manufacturer to produce and market the software, making it available to potential end-users.
3. Work with engine manufacturers to refine maintenance scheduling bulletins.
4. Copyright their database and any resulting software.

5. Reach out to biomass developers and their trade associations, such as the California Biomass Alliance, to promote interest in the software and database.
6. Partner with engine manufacturers to optimize one or more efficient emission levels for an industrial natural gas engine when operating on a variety of producer gas/natural gas mixtures.
7. Extend the neural network approach to the prediction of producer gas composition from woody biomass gasification under differing feedstock and operating conditions.
8. Document the life cycle cost and the performance of engine(s) using the new software to improve the compression ratio in terms of levelized cost of production.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.12.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system.
- Increased public safety of the California energy system.
- Increased reliability of the California energy system.
- Increased affordability of energy in California.

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system. California has approximately 225 billion cubic feet/year of gas-equivalent woody biomass available for resource recovery.[15] This resource is comprised of forest, agricultural, and municipal waste amenable to conversion to producer gas but is currently limited by the lack of economic and efficient conversion technology. Improving the efficiency of using the producer gas by 20 percent would provide for more ready acceptance of producer gas in place of natural gas. Assuming 20 percent of this resource is captured economically and 20 percent efficiency is realized, this technology could offset 9

15 http://energy.ucdavis.edu/files/05-13-2013-2012-01-summary-of-current-biomass-energy-resources.pdf converted from electrical potential to natural gas equivalent at 90 percent capacity factor and 10,000 btu/kwh heat rate.

billion cubic feet of natural gas annually. If applied to all natural gas generators in California, this could reduce the carbon footprint of electricity generation by about 1.0 percent, and possibly put a slight downward pressure on delivered natural gas prices by easing delivery constraints. California uses just over 2,300 billion cubic feet (BCF) per year of natural gas with over 1,000 BCF/year used for electricity generation.

In addition to improved efficiency in reciprocating engines using producer gas, this technology could be useful in other prime mover types (e.g., combustion turbines requiring flame stability calculations), further accelerating the development of producer gas fueled power generation systems with associated on-site displacement of natural gas.

2.12.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers did not conduct a market assessment nor had they contacted industrial companies that might take this concept to market.

Engineering/Technical

The researchers estimated that they need about $500,000 and two years to complete product and database development.

Legal/Contractual

The researchers had not performed a patent search, had not applied for patents, nor had they sought copyright protection.

Environmental, Safety, Risk Assessments/ Quality Plans

These plans have not been addressed.

Production Readiness/Commercialization

The researchers do not plan to commercialize this product. They indicated they would partner with an engine manufacturer.

2.13G Waste Heat Reformation of Renewable Feedstock to Offset Natural Gas

Awardee: Humboldt State University

Principal Investigator: David Vernon

2.13.1G Abstract

This project demonstrated that waste heat-driven chemical conversion of biomass-derived feedstock to hydrogen in water in the presence of a catalyst is technically feasible. In contrast to conventional waste heat recovery that produces hot water or steam, this approach produces hydrogen that can be used as a fuel. The project showed high conversion of sorbitol, a biomass derivable sugar, to hydrogen-rich gas at a relatively high concentration. This approach produced hydrogen that can be used to supplement natural gas in internal combustion engines to reduce emissions of nitrous oxides. The method, while maintaining low emissions of other criteria pollutants, produces with increased efficiency. The researchers showed that a recirculating operation increased conversion rates for all catalysts tested. The research team developed thermodynamic and economic models that suggest this approach may provide a biomass-to-energy option at a lower cost than other waste heat recovery systems.

Keywords: Chemical reaction waste heat recovery, aqueous phase reformation (APR), hydrogen production, hydrogen-enriched combustion, biomass-derived feedstock

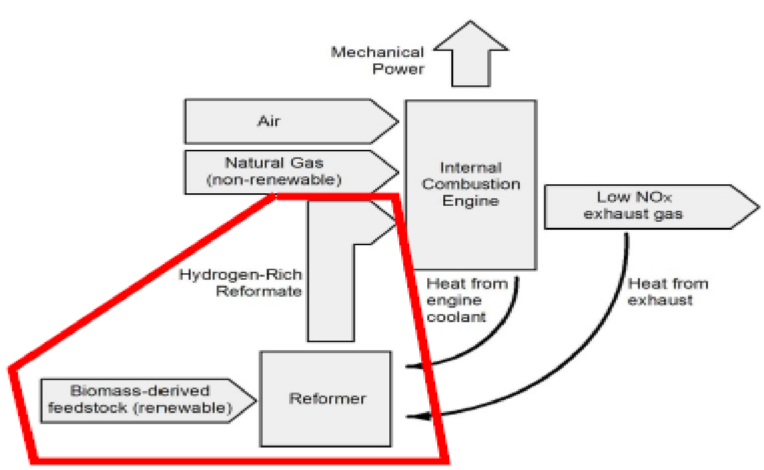
2.13.2G Introduction

The cost, stability, and efficiency of options to meet California's aggressive goals for renewables need to be improved significantly. Any method to introduce more renewables into the existing infrastructure using existing resources has built-in cost advantages.

Aqueous phase reformation (APR) is an alternative to vapor phase reformation (VPR) processes currently being researched for chemical reaction waste heat recovery. Both systems use recovered waste heat to drive chemical reaction making hydrogen, hence the name "reformation". In essence, these systems convert waste heat into chemical energy. However, VPR cannot easily process low cost biomass-derived feedstock and requires that the biomass be pre-processed to direct replacement fuels such as ethanol or methanol. Also, VPR processes require significantly higher waste heat temperatures, limiting the total amount of waste heat that can be recovered and converted into chemical energy. APR-based recovery has the potential to recover up to three times more waste heat than the VPR processes currently being researched because of lower waste heat temperature requirements. The hydrogen may be used in existing internal combustion or combustion turbine systems as a direct supplemental fuel.

Researchers evaluated the feasibility of chemical reaction waste heat recovery using aqueous phase reformation of a renewable biomass-derived feedstock to produce hydrogen. This process converts thermal energy into chemical energy producing hydrogen with more chemical energy than the feedstock. The hydrogen can then be used to enhance combustion to offset fossil fuel consumption, increase efficiency, and reduce emissions in existing engines at electrical power plants and natural gas pipeline compressors. A process diagram for this system is shown below in Figure 18. The subject of the project is outlined in red.

Figure 18: Process Diagram Showing Chemical Reaction Waste Heat Recovery Integrated with an Internal Combustion Engine



2.13.3G Objectives

The goal of this project was to determine the feasibility of aqueous phase reformation (APR) of renewable feedstock to convert waste heat as chemical energy in the form of a hydrogen-rich gas. The researchers established the following objectives:

1. Demonstrate APR with recirculating operation, verifying through observation that only gas phase products leave the reactor, with all liquid phase effluent recirculating.

2. Demonstrate gas composition measurements of H_2, CO, CO_2, and methane to within 4.0 percent by calibrating with known standards.

3. Demonstrate conversion of greater than 80 percent of the carbon in the feedstock into gas-phase carbon in recirculating operation at reaction temperatures below 280° C.

4. Demonstrate product gas production with greater than 45 percent hydrogen concentration in the gas products on a dry basis.

5. Demonstrate conversion of heat into chemical energy for a total increase in chemical energy of at least 5.0 percent.

6. Monitor for the production of desirable or undesirable side products in liquid and gas effluent.

7. Monitor for catalyst degradation over time.

2.13.4G Outcomes

1. The research team designed, fabricated, and tested a laboratory-scale recirculating reactor. The researchers observed that all liquid effluent recirculated, while gas phase products left the reformer.

2. The researchers calibrated gas composition measurement systems using both a micro gas chromatograph and a continuous process gas analyzer to within +/- 3.0 percent and +/- 2.0 percent, respectively, using known standards.

3. The researchers employed a commercially available Pt/Al_2O_3 catalyst and achieved a conversion of up to 27 percent of sorbitol into gas phase products with one pass through the catalyst bed. By recirculating the effluent liquid, the researchers converted up to 51 percent of the sorbitol. The research team synthesized two additional catalysts: Pt/carbon and Pt-Re/carbon. With the Pt-Re/carbon catalyst, the researchers achieved up to 94 percent conversion in once-through operation at 265° C and 825 pounds of pressure. Using the Pt/carbon catalyst achieved a conversion of up to 62 percent in once-through operation and up to 90 percent in recirculating operation at 265° C.

4. Using the Pt/Al_2O_3 , Pt/carbon, and Pt-Re/carbon catalysts, the researchers produced hydrogen concentrations of 43 percent, 64 percent, and 32 percent, respectively.

5. Using the Pt/Al_2O_3, Pt/carbon, and Pt-Re/carbon catalysts, the researchers demonstrated an increase in chemical energy of 11 percent, 37 percent, and 14 percent, respectively, through the conversion of heat to chemical energy.

6. The researchers monitored and tested for side products in the gas stream. The primary gas phase products other than hydrogen and carbon dioxide were alkanes: methane, ethane, and propane. The Pt/Al_2O_3 catalyst had low production of alkanes, Pt/carbon showed moderately low production of alkanes, and Pt-Re/carbon showed moderate production of alkanes, as shown in Table 3. Numerous reaction intermediate and side product chemical species were found in the liquid effluent by GC-MS[16] analysis. The compounds detected in the GC-MS analysis included unreacted sorbitol, isosorbide, ketones, carboxylic acids (formic acid, acetic acid, propanoic acid, and hexanoic acid), and diols (propylene glycol, ethanediol, and butanediol).

Table 3: Average Gas Composition from Testing

Catalyst	Sorbitol Concentration, wt%	Gas Composition, mole %									
		225°C					265°C				
		H2	CO2	CH4	C2H6	C3H8	H2	CO2	CH4	C2H6	C3H8
Pt/Al_2O_3	1%	43%	52%	1%	1%	2%	34%	61%	2%	1%	2%
	10%						14%	81%	1%	1%	3%
Pt/C	1%						64%	25%	6%	3%	2%
	10%						55%	34%	6%	3%	2%
PtRe/C	1%	19%	49%	10%	8%	13%	32%	39%	11%	7%	10%
	10%	18%	68%	5%	4%	5%	17%	62%	5%	6%	9%

Grey boxes indicate areas where results were not measured due to equipment limitations with low gas production rates at low temperatures.

7. The researchers confirmed that the Al_2O_3 catalyst was not mechanically stable under the conditions tested, and its performance declined over approximately 100 hours. The researchers did not report on the carbon-based catalyst performance or mechanical stability over time.

2.13.5G Conclusions

1. The researchers designed and fabricated a laboratory-scale reformer capable of converting sorbitol in aqueous solution to hydrogen with high efficiency, using Pt:C and Pt-Re:C catalysts. The reformer was capable of operating in a recirculating mode. The researchers completed this objective. Visual observation confirmed that gaseous products were free of liquid carryover.

16 GC-MS= gas chromatography combined with mass spectrometry.

2. Gas and liquid compositions were determined with appropriate accuracy and precision as determined by gas chromatography and on-line gas analysis. The researchers completed this objective.

3. Catalyst efficiency was better with the researcher-synthesized catalyst compared to the commercial catalyst, likely due to higher platinum loading. Conversion efficiency of 90 percent was possible in recirculating operation. The researchers completed this objective.

4. The different catalysts produced different concentrations of hydrogen in the gas stream. All concentrations, the lowest of which was 32 percent, could be used as supplemental fuel in reciprocating engines or combustion turbines. The researchers completed this objective.

5. The reforming process successfully converted a portion of the thermal energy, replicating captured waste heat into chemical energy. The researchers completed this objective.

6. The production of side products in the gas stream did not appear troublesome for combustion purposes since the side products themselves are combustible, but they may affect emissions. There are a number of side products in the recirculating liquid phase that need to be studied for their effect on catalysts and overall performance. The researchers completed this objective.

7. The mechanical integrity of the tested catalysts is a concern, with breakdown over relatively short time scales. Performance needs to be maintained, or reclaimed, over longer periods to demonstrate commercial viability. The researchers completed the objective of monitoring catalyst degradation.

The researchers demonstrated the technical feasibility of aqueous phase reforming of one simple sugar alcohol derivable from biomass feedstock to hydrogen using waste heat recovery. They have not yet demonstrated technical practicality.

2.13.6G Recommendations

The Program Administrator recommends the following actions:

1. Investigate additional sugars, including mixed sugars, which can be derived from biomass feedstock.

2. Improve the mechanical stability of catalyst substrate under the conditions likely to be encountered in aqueous phase reformation under pressure. This work should include other substrates as well as structure. Honeycomb support structure may provide more stability than packed pellets.

3. Investigate different catalysts and catalyst loading.

4. Investigate root cause analysis of performance degradation of catalysts to develop life-extending protocols. Determine if various poisoning agents are in the recirculated aqueous phase.
5. Scale up the testing from laboratory scale.
6. Perform a life cycle systems analysis and determine life cycle cost including, but not limited to, delivery mechanisms for distribution of biomass-derived sugars to locations considered for waste heat recovery. This should include a market assessment that differentiates based on temperature of waste heat and location of existing capital plant. Delivery and storage for a remote natural gas compressor station would be significantly different than a factory installed engine.
7. Determine specific engine requirements for gaseous (hydrogen) fuel streams.
8. Determine if the liquid effluent needs special handling or treatment as it contains a number of constituents that cannot be disposed of directly. The liquid effluent may pose an attractive nuisance to wildlife and domestic animals if not disposed of properly.
9. Develop a quality plan for the catalyst. It should include a protocol for reactivation of the catalyst.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.13.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system.
- Increased public safety of the California energy system.
- Increased reliability of the California energy system.
- Increased affordability of energy in California.

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system.

Chemical reaction waste heat recovery in natural gas engines displaces fossil fuels and abates GHG emissions by producing energy from a renewable, biomass-derived feedstock. The research team's economic analysis estimated that APR waste heat recovery would have an installed cost as low as $1,500 per kW of incremental generation compared to current costs for new biomass power plants of $3,400 to $4,250 per kW installed.[17] APR waste heat recovery enables utilization of biomass-derived feedstock in existing power plants with the potential to produce low or net zero carbon electricity at much lower costs than building new dedicated biomass power plants.

If this hydrogen-enriched natural gas were used to fuel the 460 MW capacity of natural gas internal combustion engine power plants currently operating in California, APR waste heat recovery could displace 106 million therms of natural gas per year. This would save power producers over $47 million per year on natural gas costs. Assuming that biomass is carbon neutral, this technology eliminates 563,000 metric tons of CO_2-equivalent emissions annually, saving power producers an additional $6.4 million in emission allowances. Based on the estimated 95 percent nitrous oxides (NO_x) emission reductions resulting from hydrogen enrichment, 1,900 metric tons of NO_x could be avoided.

Potential feedstock supply markets include biomass-derived cellulosic sugars, unfermentable sugars from ethanol production, and waste sugars from the food industry such as breweries, wineries, and food processing, as well as crude glycerol, a byproduct of biodiesel production.

2.13.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have discussed the results of their research with Caterpillar, Inc., but have received no firm commitments for joint development. At the close of this project the researchers had not approached potential customers such as wineries, breweries, and food processors.

Engineering/Technical

The researchers estimate that they will need about seven years and over $10 million to complete the technology development and demonstration.

Legal/Contractual

The researchers have completed a self-search for conflicting patents. It is not yet clear if the proposed technology will infringe on any other active or expired patents. Further patent search is required. They have identified patentable technology.

Environmental, Safety, Risk Assessments/Quality Plans

These tasks had not been scheduled into this project. They are very critical to the success of any product and must be addressed.

---

17 Gibson, Laura (2011). Comparing Costs. Biomass Magazine. Accessed August 8, 2014 http://biomassmagazine.com/articles/5926/comparing-costs

Production Readiness/Commercialization

The concept is not yet ready for commercialization or production.

2.14G Two-Track Heat Storage: Very Hot Solar Thermal Storage

Awardee: Rolf Miles Olsen

Principal Investigator: Rolf Miles Olsen

2.14.1G Abstract

The researchers in this project proposed a novel two-track heat transfer approach that would enable very high temperature thermal storage. Potential applications for the storage would be in focused solar power tower systems or as a solar-powered preheater in utility-scale fossil fuel powered electrical generators. The high temperature was made possible by storage in the form of sensible heat in a thermally stable packed bed of solids and with heat transferred by air. The key innovation was a modified two-track gas flow through the packed bed. The researchers showed that for equal applied dynamic air pressures, the two-track apparatus achieved higher air mass flow rates through packed beds than standard packed beds without the two-track approach. Significantly, air mass flow rate through a two-track packed bed was largely unaffected when the length of this packed bed was doubled from approximately 7′ to 14′, even though the applied dynamic air pressure across the two bed lengths was the same. For any given applied dynamic pressure across a packed bed, tall two-track packed beds would be capable of achieving nearly equal intensive (per unit cross sectional area)) air mass flow rates compared to those of much shorter standard packed beds. The researchers therefore concluded that two-track packed beds could be made much longer, in the order of 50′, for use in very large heat storage applications. Because of the economies of scale, this would lower the costs of pressurized heat storage units using the two-track approach relative to those using standard packed beds.

The research satisfied the modest goals of the proposed Statement of Work. The tests were carried out under room temperature 300K isothermal conditions. However actual operation would be at 1,000K or higher and with large gas temperature swings through the bed. The researchers only simulated these conditions in a model with the Schuman equations. The model results did give insight on potential bed materials, but feasibility proof will require experimental testing at elevated temperatures with actual materials.

Keywords: Two-track flow, packed bed, dynamic air pressure, air mass flow rate, heat storage, power tower

2.14.2G Introduction

Large-scale use of solar energy to reduce greenhouse gas emissions from electrical generators has been limited by the need for energy storage for overnight power and for operator-controlled dispatchability. A scalable thermal storage reservoir capable of delivering stored solar energy at high temperature would satisfy this need and displace consumption of natural gas fuel. There are two important applications for such a reservoir, both of which serve to reduce consumption of natural gas in California.

The first is the concentrated solar power tower system in which a field of tracking mirrors focuses concentrated sunlight on a raised central absorber. The absorber transfers heat to a thermal reservoir sometimes in the form of a eutectic fused salt mixture that melts at high temperatures and has high heat capacity. Because the heat storage medium is a compact liquid rather than a large solid, it greatly increases the ease of transferring stored energy.

The second application for a solar thermal reservoir is a hybrid preheater of combustion air for natural gas-fired electrical generators.[18] In 2012 natural gas provided 61.1 percent of California's in-state electricity.[19] A gas turbine combined cycle with a Brayton turbine topping cycle and a Rankine bottoming cycle is a candidate for solar preheat. These systems offer high system efficiency of 61 percent with low capital cost per watt output.[20] The researchers claimed that the use of high temperature solar preheating could displace >50 percent of the natural gas requirement, with potential savings in operation cost and avoided emission of carbon dioxide per unit of electrical output.[21] A problem with the high temperature liquid salt-based storage media is that it is very corrosive and tends to decompose, affecting its performance and limiting system efficiency. Heat storage in the sensible heat capacity of a solid material could be at a much higher temperature and would be much less corrosive and less susceptible to decomposition. Heat could be transferred in and out by forcing heat transfer gas through a packed bed of solid pebbles, for example. Because it has a low heat capacity per unit volume, transfer gas requires elevated pressure and high volumetric flow rates for adequate heat transfer rates. High gas flow rates through the entire packed bed would require large pressure differences with large parasitic losses in energy for pumping, which would limit performance. If a means could be found to circumvent these gas pumping losses in packed beds, it would allow the solar heat storage temperature to be raised to much higher values with concomitant increase in thermal-to-electric conversion efficiency and lower cost per unit output.

With such a means thet benefits to California ratepayers could be measurable in the form of reduced GHG emissions and lower cost solar-to-electric conversion. To set the scale for the

---

18 http://gasturbinespower.asmedigitalcollection.asme.org/mobile/article.aspx?articleid=1763541

19 http://energyalmanac.ca.gov/electricity/total_system_power.html

20 http://www.eia.gov/forecasts/aeo/pdf/0383(2012).pdf, see fig.98

21 http://www.cleanskies.org/wp-content/uploads/2012/04/Turchi_CERF3_04192012.pdf

potential GHG reduction, it is useful to note that in 2012 in-state system power for California was 199,000 gigawatt hours (GWh) and 302,000 GWh including imports from out of state. Overall, renewable energy accounted for 15.4 percent of this total consumption, but the solar contribution was only 0.9 percent. Going forward, California's Renewables Portfolio Standard (RPS) requires investor-owned utilities, electric service providers, and community choice aggregators to increase procurement from eligible renewable energy resources to 33 percent of total procurement by 2020.[22] Thus approximately18 percent of new renewable system power will need to be brought online by 2020. At 2012 levels of consumption, 18 percent of the total would be 54,360 GWh. Assuming a market penetration of just one quarter of the 18 percent for systems with high temperature, solar thermal storage would represent 13,590 GWh. The average CO_2 emission factor for natural gas powered steam-electric generators (2012) was 1.22 lbs/kWh.[23] The assumed saving of 13,590 GWh corresponds to a savings of at least 8.3 MMTMMT of GHG emission. The economic value to the ratepayer would also be significant. The current average price of electricity to the California ratepayer is 15.2 cents/kWh.[24] At this rate the economic value of the solar contribution could be as high as $2.1B per year. Cost of additional capital equipment and increased maintenance costs could reduce that savings. Thus, in addition to the reduction in GHG emissions, there could be a measurable fuel cost saving with the introduction of a solar thermal reservoir.

The researchers noted that the heat storage process in a storage tank involves the movement of a zone of large thermal gradient, a thermocline, as shown on the left side of Figure 19. During charging of the tank the thermocline moves down until the tank is fully charged at a high temperature. During discharge through a heat engine, the thermocline moves up until the tank is fully discharged at the exhaust temperature of the engine. When the transfer gas passes through the approximately isothermal zones above and below the thermocline there is very little heat transferred to the gas from the packed bed. Although there is little heat transfer in the isothermal zones, there is still significant wasted pumping loss to force the gas through these zones. The advancement of science proposed in this project to circumvent these pumping losses was a two-channel gas flow path with low resistance perforated tubes running through the tank as shown on the right side of Figure 19. Movable plugs in the central tubes diverted gas flow out of the tube into the packed bed through the thermocline region. Once past the diverter plugs, the gas re-entered the perforated tube. During charging and discharging the movement of the diverter was controlled to follow the moving thermocline, as indicated in the Figure. In this way heat was transferred to the gas, but the gas flowed through the isothermal zones with the attendant pumping losses eliminated.

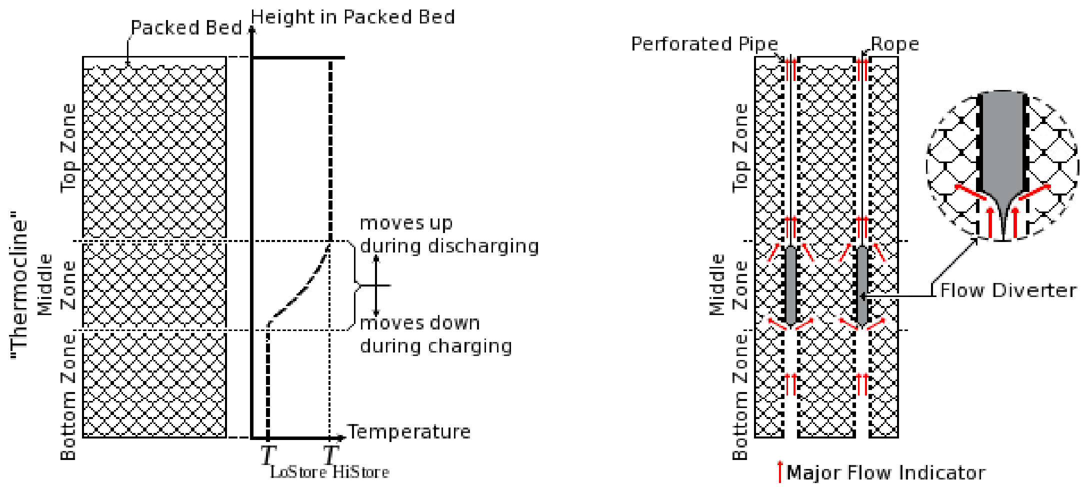
---

23 http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11

23 http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11

24 http://www.npr.org/blogs/money/2011/10/27/141766341/the-price-of-electricity-in-your-state

Figure 19: Schematic of Two-Track Heat Storage Device



Left Figure 19 illustrates the moving thermocline middle zone of standard packed bed heat storage. The packed bed material in the bottom zone is at constant low storage temperature, while the material in the top zone is also at constant temperature but at the high storage temperature. Heat transfer fluid flows vertically through the packed bed without exchanging heat with the packed bed material in the top and bottom zones, but when in the middle zone it exchanges heat with the bed material to either add heat to the bed material when flowing downwards during heat charging or to take heat away from the bed material when flowing upwards during discharges. The two-track heat storage with flow diverters is illustrated in right Figure 19.

2.14.3G Objectives

The goal of this project was to determine the feasibility of adding new fluid flow devices into packed bed heat storage units to make heat storage units that can integrate with utility-scale solar thermal power plants at low cost and across a wide range of temperatures, including those too high for state-of-the-art molten salt heat storage. The researchers established the following project objectives:

1. Build a predictive model of two-track heat storage performance that is implemented on a computer.
2. Finalize the test rig design.
3. Make small, specialized two-track components for the test rig.
4. Purchase and customize components for the test rig. Mount all components on the rig stand and connect them to fabricate the test rig.
5. Install and calibrate the test stand instrumentation to measure gas pressure and mass flow rates. Demonstrate that the test stand is capable of measuring pressures to better than +/- 5 Pa resolutions and intensive mass flow rates of better than +/-0.03 kg/(s m^2).
6. Finalize test plan. Obtain EISG Program Administrator approval of test plan.

7. Conduct testing on the test rig and the predictive model. Demonstrate the two-track test rig will perform:

    - with bigger gas flow rates than standard packed beds.
    - with gas mass flow rates affected to less than 0.03 kg/(s m^2) detectable changes by adding two 3′ lengths to the test rig.
    - with ambient temperatures achieve 0.4 kg/(s m^2) air flow rates through the 12′ rig with 1,500Pa pressure drop or less.

    Demonstrate the model can predict test rig experimental performance when both are run under uniform temperature conditions.

8. Perform manufacturing and installation cost analysis. Confirm from the project findings that projected manufacturing and installation cost of \$15/kWh_t continues to be supported or bettered.

9. Perform life cycle cost analysis. Confirm from the project findings that projected life cycle cost of \$0.05 per kWh year continues to be supported.

2.14.4G Outcomes

1. The researchers developed a computer model of two-track heat storage performance to predict local pressure differences in a two-track packed bed with gas flowing through it.

2. The researchers designed a test rig.

3. They manufactured specialized components for the test rig. They acquired a vitreous clay pipe for the central tube, but it proved too difficult to perforate by drilling. A section of PVC pipe was substituted and drilled with holes.

4. They customized purchased components for the test rig. All components were assembled on the test rig.

5. The researchers instrumented the test stand to measure gas pressure and mass flow rates. Pressures were measured to better than +/-1.6 Pa resolution and intensive mass flow rates to better than +/-0.03 kg/(s m2).

6. The researchers developed a final test plan. It was not clear that they obtained approval of an EISG Program Administrator.

7. The researchers compared performance of the test rig with the model predictions. They demonstrated that the two-track test rig performed with bigger gas flow rates than standard packed beds. Comparison tests between two test units, a 7′6″ and 13′6″ two-track, showed that gas mass flow rates were affected to less than 0.03 kg/(s m2). Tests on the 13′6″ two-track test bed achieved a 0.54 kg/(s m2) air flow rate with a 1,688 Pa pressure drop. The computer model contained four adjustable parameters. The researchers placed an array of pressure sensors in the test bed and adjusted the

parameters to maximize model fit to the pressure data. All tests were under isothermal conditions at room temperature.

8. The researchers estimated manufacturing and installation costs between \$6.06/kWh and \$7.76/kW for the four cases considered.
9. Life cycle cost analysis demonstrated a cost of \$0.03 per kWh year for maintenance repair and replacement.

2.14.5G Conclusions

1. The researchers successfully developed a computer predictive model of two-track heat storage performance to give local pressure differences in a two-track packed bed with gas flowing as proposed. Thus this goal was met. However, it was not clear by comparison with the experiment if the model could account for non-isothermal conditions which result in heat flows and large gas volume changes through the thermocline in an actual application.
2. The researchers successfully designed a test rig.
3. The researchers successfully developed specialized components for the test rig as proposed. Since the vitreous clay pipe proved too difficult to drill, the researchers substituted a section of PVC pipe and drilled it with holes. While the PVC pipe was adequate for the room temperature testing that was done, it will need to be replaced later, perhaps by clay pipe perforated before firing.
4. The researchers successfully assembled all customized components assembled on the test rig. Thus this goal was met.
5. The researchers instrumented the test stand. Measurements demonstrated that gas pressure and mass flow rate goals were successfully met.
6. The researchers successfully developed a final test plan.
7. Isothermal tests on two different length two-track test units demonstrated that the flow rate was virtually unaffected by track length. This was an important result, but it will need to be replicated under high temperatures and with high temperature gradients. The researchers met the goal to estimate manufacturing and installation costs.
8. Estimated life cycle cost goals for maintenance repair and replacement were met.

The research satisfied the modest goals of the proposed Statement of Work. The tests were carried out under room temperature 300K isothermal conditions. However, actual operation will be at 1,000K or higher and with large gas temperature swings through the bed. The researchers only simulated these conditions in a model with the Schuman equations. The model results did give insight on potential bed materials, but proof of feasibility will require experimental testing at elevated temperatures with actual materials.

2.14.6G Recommendations

The Program Administrator recommends that the researchers be more aggressive in testing at higher operating temperatures and with candidate materials. They have stated concerns about sensor survivability at elevated temperatures. That should not be a serious concern with temperature sensors such as platinum resistance sensors or platinum-rhodium thermocouples. Gas mass flow sensors should be able to be modified for high temperature use or cooled and corrections applied to their output.

In addition the researchers should:

- Evaluate the cost to incorporate a heat exchanger into an advanced large-scale gas turbine engine.
- Investigate the need for high temperature valves.
- Evaluate the cost and design of high pressure transition ducts.
- Develop preliminary control schemes for a hybrid energy system.
- Evaluate pressure drops throughout the gas turbine flow path to ensure proper operation at all conditions.
- Evaluate capital cost impacts of the hybrid system.

2.14.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system.
- Increased public safety of the California energy system.
- Increased reliability of the California energy system.
- Increased affordability of energy in California.

The benefits to California ratepayers could be measurable in the form of reduced GHG emissions and lower cost solar-to-electric conversion. Overall, renewable energy accounted for 15.4 percent of total power consumption in California in 2012, but the solar contribution was only 0.9 percent. Going forward, California's Renewables Portfolio Standard requires investor-owned utilities, electric service providers, and community choice aggregators to increase procurement from eligible renewable energy resources by approximately 18 percent by 2020. At 2012 levels of consumption, 18 percent of the total would be 54,360 GWh. Assuming a market penetration of just one quarter of the 18 percent for systems with high temperature, solar thermal storage would represent 13,590 GWh. The average CO_2 emission factor for natural gas powered steam-electric generators (2012) was 1.22 lbs/kWh.[25] The assumed saving of 13,590 GWh corresponds to a savings of at least 8.3 million metric tons of GHG emission. The economic value to the ratepayer would also be significant. The current average price of electricity to the California ratepayer is 15.2 cents/kWh.[26] At this rate the economic value of the solar contribution could be as high as $2.1B per year. Cost of additional capital equipment and increased maintenance costs could reduce that savings. Thus, in addition to the reduction in GHG emissions, there could be a measurable fuel cost saving with the introduction of a solar thermal reservoir.

The primary benefit to the ratepayer from this research could be reduced environmental impacts of the California energy supply and distribution system. If the problem is solved, the benefits to the California ratepayer could be measurable in the form of reduced GHG emissions and lower fuel costs. To set the scale for the potential GHG reduction, it is useful to note that in 2012, in-state system power for California was 199,000 gigawatt-hours (GWh) and 302,000 GWh including imports from out of state. Overall, renewable energy accounted for 15.4 percent of this total consumption, but the solar contribution was only 0.9 percent. Going forward, California's RPS requires investor-owned utilities, electric service providers, and community choice aggregators to increase procurement from eligible renewable energy resources to 33 percent of total procurement by 2020.[27] Thus approximately 18 percent of new renewable system power will need to be brought online by 2020. At 2012 levels of consumption, 18 percent of the total would be 54,360 GWh. Assuming a market penetration of just one quarter of the 18 percent for systems with high temperature, solar thermal storage would represent 13,590 GWh. The average CO_2 emission factor for natural gas-powered steam-electric generators was 1.22 Lbs/kWh.[28] The assumed saving of 13,590 GWh corresponds to a savings of at least 8.3 million metric tons of GHG emission. The economic value to the ratepayer could be significant. The current average price of electricity to the California ratepayer is 15.2 cents/kWh.[29] At that price the economic value of the savings in fuel cost to the solar contribution could be $2.1B per year. Actual savings depend on the capital and maintenance cost increases and hours run at each operating condition. Thus, in addition to potential reduction in GHG emissions, there could be fuel cost savings with the introduction of such a solar thermal reservoir.

2.14.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

25 http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11

26 http://www.npr.org/blogs/money/2011/10/27/141766341/the-price-of-electricity-in-your-state

27 http://www.cpuc.ca.gov/PUC/energy/Renewables/

28 http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11

29 http://www.npr.org/blogs/money/2011/10/27/141766341/the-price-of-electricity-in-your-state

Marketing/Connection to the Market

The researchers had not surveyed potential customers nor performed a market analysis by the end of this project. At the end of the project they were in the process of trying to reach an agreement with a gas turbine manufacturer.

Engineering/Technical

The researchers plan to continue work on this project subject to funding. They estimate they could demonstrate a prototype in about 18 months with less than $500k dollars in funding.

Legal/Contractual

One United States Patent Application and one United States Provisional Patent Application have been filed. The researchers are partnering with a large civil engineering consultancy (Moffat and Nichol) and a gas turbine research company (Brayton Energy) on an application to United States Department of Energy Sunshot Incubator funding.

Environmental, Safety, Risk Assessments/Quality Plans

The researchers are aware that operation at pressures up to 8 bar will pose safety concerns that will need to be addressed.

Production Readiness/Commercialization

It is premature to begin commercialization efforts until the technology is demonstrated at realistic temperatures and pressures.

2.15G Earth-Abundant and Scalable Nanostructured Thermoelectrics for Energy Harvesting

Awardee: The Regents of the Univ. of California, University of California, San Diego

Principal Investigator: Renkun Chen

2.15.1G Abstract

Waste heat from natural gas power plants is a significant potential energy resource. The exhaust heat from natural gas engines and turbines is discharged at relatively high temperatures and therefore can be partially recovered. The goal of this project was to develop a new class of thermoelectric (TE) materials, based on nanostructures of earth-abundant, low cost magnesium silicide-based materials (Mg-Si-Sn) which could be used to recover energy from power plant waste heat and other heat sources such as vehicular, solar thermal, and industrial process waste heat.

The TE figure of merit (ZT) determines TE conversion efficiency and depends inversely on the material's thermal conductivity. Thermal conductivity is lowered in materials with small grain size due to phonon-grain boundary scattering. Researchers in this project identified the optimal nanostructured grain size of Mg-Si-Sn by a theoretical model study. The researchers fabricated Mg-Si-Sn nanoparticles with grain size less than 20 nm using a new scalable spark erosion synthesis technique. They then consolidated the nanoparticles produced into bulk-shaped pellets which they measured for their relevant TE properties. Compared to bulk Mg-Si-Sn, they observed significantly reduced thermal conductivity and a modestly higher ZT. This indicated feasibility of the spark erosion approach to higher ZT.

A cost analysis of the thermoelectric waste heat recovery based on the Mg-Si-Sn nanoparticle materials showed that there is significant performance/cost potential of TE waste heat recovery based on the new materials. The researchers concluded that with further work, thermoelectric generators based on silicide materials could provide a very attractive low-cost option for waste heat recovery.

Keywords: Thermoelectric, waste heat recovery, spark erosion, nanostructures, magnesium silicide

2.15.2G Introduction

The objective of this project was to enable the recovery of energy otherwise lost in waste heat. Any energy conversion process that involves heat results in the production and loss of waste heat energy. There are many sources of waste heat such as natural gas (NG) and coal-powered electric generators, fossil-fueled vehicles, and industrial processes. This waste heat is a valuable potential resource.[30] Generally, waste heat is released at low temperatures, sometimes below 200° C, which has made it extremely difficult to harvest for practical electricity generation. An attractive method of recovering this otherwise lost energy would be to convert it directly to electricity with a thermoelectric (TE) material. However, all of these efforts have been hampered by the low efficiency of conversion and the high cost. The efficiency of a TE material is determined by the TE figure of merit, ZT. ZT is defined as

$$ZT = S^2 \sigma T / \kappa$$

where S is the Seebeck coefficient, σ is electrical conductivity, T is the absolute temperature, and κ is the thermal conductivity. Known high efficiency TE materials have a ZT of 1—2 and are composed of high cost elements. The goal of this project was to develop a high efficiency TE material with ZT approaching 2 that was composed of low cost elements.

The advancement proposed in this project was to increase ZT by a novel spark erosion technique that would produce ultrafine nanoparticles of TE materials. Doped semiconductors are a promising class of materials for TE applications since S is relatively large and by judicious doping can be increased to larger values without too great a penalty in decreasing S. This project proposed maximizing ZT by minimizing κ. The dominant contribution to κ in doped semiconductors is the lattice thermal conductivity in which heat is carried by phonons. In polycrystalline materials the lattice thermal resistivity, 1/κ, is the sum of two phonon scattering processes, one in the thermal resistance in bulk of a grain and another in the scattering of phonons at boundaries between grains. The approach taken in this project was to develop a novel process to synthesize a promising TE material in an extremely fine grain microstructure so that κ is limited by phonon scattering at the grain boundaries. The researchers chose the starting material $Mg_2Si_xSn_{1-x}$ because it has shown a relatively high ZT (~1.1) in its bulk form at ~800 K, a desirable temperature for waste heat recovery, and it is inexpensive.

The novel spark erosion synthesis approach for fine particles is shown schematically in Figure 20. The researchers submerged two electrodes of the TE material in a dielectric liquid in a container that was connected to a high power electrical supply. They vibrated the container so that random contacts among the electrodes were made and broken frequently. When the gaps among the electrode charge pieces were small enough so the electric field across them was larger than the dielectric breakdown field, a spark, micro-plasma, was produced between the pieces. This micro-plasma consisting of electrons and positive ions of electrodes and the

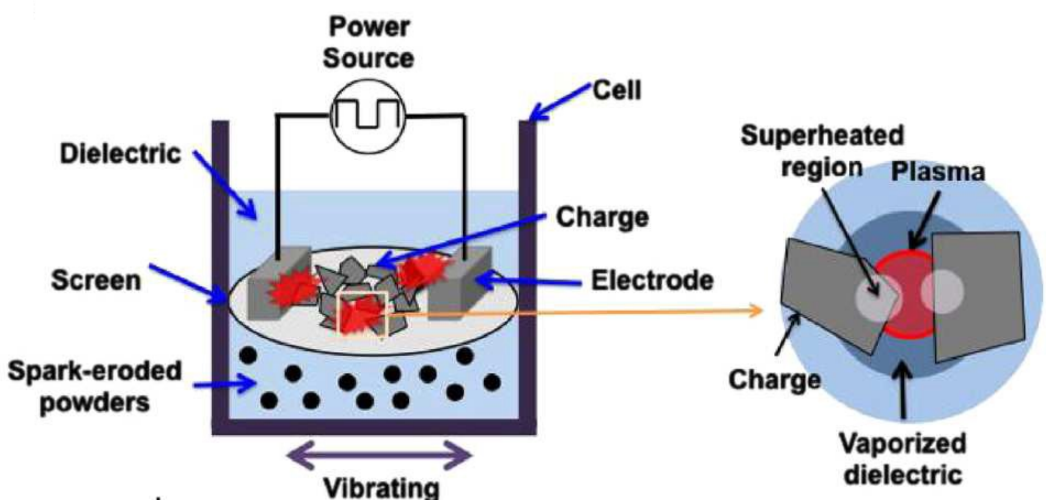
28 http://en.wikipedia.org/wiki/Waste_heat

dielectric liquid was very hot, in the order of 10,000 K. When the spark collapsed, vaporized alloy and molten droplets were violently ejected from the hot regions into the dielectric liquid. In the dielectric liquid they were rapidly quenched and fell to the bottom as very small nanoparticles. The fine nanoparticles could then be pressed into fine-grained TE elements for testing and applications. In addition, it should be possible to add another nanoparticle component by co-spark erosion to form nanoparticle composite mixtures.

2.15.3G Objectives

The goal of this project was to determine the feasibility of a new class of thermoelectric materials and devices based on nanostructures of earth-abundant magnesium silicide, which could be used to harvest energy from various heat sources such as vehicular, solar, thermal, and industrial waste heat. The researchers established the following project objectives:

Figure 20: Schematic Diagram of the Spark Erosion Process



1. Identify optimum materials composition and structures of Mg-Si-Sn using modeling. The goal is to demonstrate a thermoelectric figure of merit > 2.

2. Fabricate silicide nanoparticles by spark erosion. Demonstrate nanoparticles with < 50 nm particle size and < 20 grain size.

3. Incorporate insulating nanoparticles into thermoelectric particles. Demonstrate a uniform dispersion of 2—5 nm SiO_2 nanoparticles in Mg-Si-Sn particles.

4. Increase the spark erosion yield for Mg-Si-Sn. Demonstrate a yield higher than 100 gram/hour.

5. Consolidate the Mg-Si-Sn nanopowders by hot pressing. Demonstrate oxidation-free, high density hot pressing with porosity < 3.0 percent.

6. Measure thermoelectric properties of the hot pressed pellets. The thermoelectric figure of merit should be > 2.

7. Perform cost analysis of the thermoelectric waste heat recovery based on the Mg-Si-Sn nanocomposites. Confirm a high performance to cost ratio of < $1/watt.

2.15.4G Outcomes

1. The researchers performed modeling on the thermoelectric performance of nanostructured Mg-Si-Sn alloy and identified the optimum nanostructure grain size for the best thermoelectric figure of merit ZT to be 2.1.
2. The researchers fabricated Mg-Si-Sn nanoparticles with sub-50 nm particle size and sub-20 nm grain size.
3. The researchers incorporated commercial 5 nm Al_2O_3 nanoparticles into the Mg-Si-Sn nanocomposite materials by spark erosion in a colloidal suspension of nanometer particles of Al_2O_3 in the dielectric liquid.
4. The researchers increased the spark erosion yield for Mg-Si-Sn by increasing spark erosion power to demonstrate a fabrication yield of 120 gram/hr for Mg-Si-Sn nanoparticles.
5. The researchers consolidated the Mg-Si-Sn nanopowders with ~3.0 percent porosity using rapid hot pressing in an oxygen-free atmosphere (<10ppm). They did not directly measure oxygen content of the pressed compacts.
6. The researchers measured the thermoelectric properties of the hot pressed pellets of n-type Mg-Si-Sn and showed a higher thermoelectric figure of merit ZT of 1.24 at 700 K.
7. The researchers performed cost analysis of the thermoelectric waste heat recovery based on the Mg-Si-Sn nanocomposites and showed that the material cost was very low at $1.12 per watt.

2.15.5G Conclusions

1. The researchers successfully identified the optimum nanostructure size for the best thermoelectric figure of merit to be ZT = 2.1. They met this objective.
2. The researchers successfully demonstrated nanoparticles with < 50 nm particle size and < 20 grain size. They achieved this objective.
3. The researchers incorporated 5 nm Al_2O_3 nanoparticles into the Mg-Si-Sn nanocomposite materials in place of 2—5 nm SiO_2 nanoparticles. Thus this objective was partially met.
4. The researchers exceeded the goal of a yield higher that 100 grams/hr of Mg-Si-Sn nanoparticles.
5. The researchers met the objective of Mg-Si-Sn nanopowder consolidation by hot pressing to about 3.0 percent porosity.
6. The researchers measured the thermoelectric properties of the hot pressed pellets of Mg-Si-Sn and showed a slightly higher thermoelectric figure of merit ZT = 1.24 at 700 K over

the bulk value of ZT = 1.1. The researchers speculated that the lattice thermal conductivity was low enough, but the electrical conductivity of the pressed nanoparticles needed to be increased. More work needs to be done to meet this important objective. The nanocomposite samples with Al_2O_3 had a lower ZT of 0.8 at 700 K.

7. The researchers performed cost analysis of the thermoelectric waste heat recovery based on the Mg-Si-Sn nanocomposites and showed that while the material cost of $1.12 /watt was very low, improvement of ZT from 1.24 to 1.4 would bring the cost below the $1/watt target. This objective was not quite, but nearly, met.

The goal of this project was to determine the feasibility of a new class of thermoelectric materials and devices based on nanostructures of earth-abundant, low cost magnesium silicide, which could be used to harvest energy from various heat sources such as vehicular, solar thermal and industrial waste heat. The researchers made a small increase in thermoelectric performance with pressed nanoparticle TE elements, which demonstrated a positive indication of feasibility.

2.15.6G Recommendations

The Program Administrator recommends that more extensive compositional studies into optimized doping of nanoparticle compositions could produce improved performance. Since the particles are very small, they have a relatively larger proportion of atoms on a grain surface with a reduced number of atomic bonds, which could shift the optimum composition for S. In addition, surface treatment before compaction and heat treatment might increase phonon scattering at grain boundaries. The researchers should also evaluate the economics of the concept when deployed at a utility-scale level.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.15.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system.
- Increased public safety of the California energy system.
- Increased reliability of the California energy system.

- Increased affordability of energy in California.

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system. If a low cost, high efficiency material could be developed, the benefits to California ratepayers would be substantial in the form of lower cost electricity and reduced emission of greenhouse gas (GHG). The amount of waste heat produced in the United States and dissipated to ambient surroundings is large. The United States national consumption of energy is about 100 quads (1 quad = 10^{15} BTU) of energy a year. Of the 100 quads of energy consumed per year nationwide, 55—60 percent gets lost as waste heat. Based on a per capita estimate, California's share of this waste heat is in the range of 5—10 quads. Ten quads is equivalent to $2.93X10^{12}$ kWh of energy. If this could be converted to electricity with 10 percent efficiency, it would represent a savings of $2.93X10^{11}$ kWh or 293,000 GWh of electricity. This savings is 147 percent of California's entire annual 2010 in-state electricity production of 199,783 GWh. The current average price of electricity for a California ratepayer is 15.2 cents/kWh. Thus, the annual economic benefit to California ratepayers could be as high as $44.5B. Of special importance is that there could be a corresponding reduction in California GHG emissions. In 2012, natural gas fueled 61.1 percent of California in-state electricity production. Since the TE conversion of waste heat to electricity results in no added GHG emissions, natural gas electricity generation's GHG emissions could be reduced to zero. Actual benefits of lower cost electricity and reduced GHG emissions would be less than this estimate, which assumes 10 percent waste heat conversion to electricity from all sources. It establishes, however, that waste heat recovery has a large potential environmental benefit to California.

2.15.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers had not surveyed potential customers nor performed a market analysis during the performance of this project.

Engineering/Technical

The researchers estimate that they need $600,000 and three years to complete the development and demonstration of this technology.

Legal/Contractual

The researchers have not applied for any patents on the technology, but they plan to do so.

Environmental, Safety, Risk Assessments/Quality Plans

It is premature to call for additional testing or plans in these areas at this stage of development.

Production Readiness/Commercialization

The researchers do not have a commercialization plan. They intend to partner with an industrial firm to take this technology to market.

2.16G Solar Thermoelectric Energy for Residential-Scale Combined Heat and Electricity

Awardee: Santa Clara University

Principal Investigator: Hohyun Lee

2.16.1G Abstract

California policymakers continue to encourage and promote the use of renewable energy resources for utility-scale projects and customer applications. Solar photovoltaic (PV) systems dominate the residential market segment, offsetting the use of electricity from the grid and lowering overall utility electric demand. On the other hand, there are a limited number of viable solar thermal system applications in the residential, commercial, and industrial marketplaces, mostly domestic hot water and pool heating applications. Residential solar thermal systems are generally not cost effective for consumers, even with the availability of incentives from the California Solar Initiative (CSI).

The goal of this project was to demonstrate the feasibility of generating heat and electricity for a single-family home using a concentrated solar power (CSP) energy system concept. Successful deployment of CSP technology has historically been limited to utility-scale power generation applications due to high capital cost requirements. Researchers in this project believed that a more cost effective CSP system could be developed through integration of inexpensive mirrors, solar tracking equipment, and thermoelectric modules. Generation of electricity was accomplished by passing heat collected by the CSP system across thermoelectric modules. Residual heat was then used to operate an absorption refrigerator and/or produce domestic hot water depending on the size of the system and individual customer needs. In this project the research team successfully fabricated and tested a one-fifteenth (1/15)-scale prototype. Test results closely matched modeling predictions by producing 3.0 watts (W) of electricity and 200 W of useful heat. Modeling work suggested that system performance could be significantly improved with better insulation and component modifications. A preliminary economic analysis predicted potential annual savings of more than $300 for a typical residential customer. The system cost needs to be reduced further in order to lower payback to four years and further work is needed to optimize system design and performance, evaluate potential manufacturing issues, and validate financial viability.

Keywords: Thermoelectric, concentrated solar power (CSP), combined heat and power (CHP), absorption refrigerator, solar tracker

2.16.2G Introduction

California policymakers continue to encourage and promote the use of renewable energy resources for utility-scale projects and customer applications. Solar photovoltaic (PV) systems dominate the residential market segment, offsetting the use of electricity from the grid and lowering overall utility electric demand. On the other hand, there are a limited number of viable solar thermal system applications in the residential, commercial, and industrial marketplaces. These are mostly used for domestic hot water and pool heating applications.

The objective of this project was to pursue development of an economically viable residential scale concentrated solar power (CSP) system using thermoelectric modules and a relatively inexpensive solar tracking device. In general, residential solar thermal systems are not cost effective for consumers, even with the availability of incentives from the California Solar Initiative (CSI). The average installed cost of a typical residential solar thermal hot water system ranges between $5,000 and $7,500. The maximum solar thermal incentive in California for single-family homes is $2,175 per residence.[31] Estimated annual consumer savings is approximately $300 per year. Thus the average payback for a residential solar thermal system is 10 years or greater.

Further development of a small, modular CSP could potentially provide residential, commercial, and small industrial customers with a more practical and cost effective solution (e.g., less than five years payback). Conventional CSP systems use mirrors to reflect solar rays into a concentrated receiver that heats a working fluid, driving an electric generating device (e.g., steam turbine or Stirling engine). Up to 75 percent of incoming solar radiation from CSP can be converted into useful energy, including the production of electricity and recovery of waste heat. Application of CST has been typically limited to utility-scale power generation[32] due to expensive parts and high installation costs. Utility-scale CSP has been successfully deployed over the past few decades using steam turbines to generate electricity.

The research team believed that CSP could be adapted to smaller customer facilities for combined cooling, heating, and power (CCHP) generation applications. Widespread adoption of small-scale CSP has not materialized, mostly due to excessive capital cost challenges. The use of small turbine technology is generally not practical for CSP because turbines are inefficient and expensive. There are a few small CSP products in the marketplace based on the use of Stirling engine modules in the size range of 3 kW, 25 kW and 100 kW.[33,34,35] However it is still

---

31 http://www.cpuc.ca.gov/PUC/energy/Solar/swh/csithermalincentives.htm

32 Northwest Research Energy Laboratory (NREL). Energy Technology Cost and Performance Data. In: NREL, editor. Golden, CO2010

33 http://investing.businessweek.com/research/stocks/private/snapshot.asp?privcapId=25182599

34 Stirling Energy Systems http://www.stirlingenergy.com

35 http://tcchan.wordpress.com/2010/07/27/heliofocus-harnesses-the-power-of-wind-and-sun-for-elctricity/

very difficult to justify the high capital cost of a Stirling-based CSP system for residential, commercial, or small industrial applications.

The research team believed that the use of solid state thermoelectric materials could help overcome key cost hurdles associated with small-scale CSP and produce a set of products which are more reliable, easily scalable, and free of vibration or noise.[36] Thermoelectric systems have been used for various industrial and deep space missions for more than 30 years. Unlike photovoltaic (PV), energy conversion efficiency of thermoelectric devices does not degrade with increasing ambient temperature, and thus the entire spectrum of solar energy can be utilized. Thermoelectric modules feature higher power density from a footprint and weight perspective and generate more power under cloudy conditions than PV cells. Thermoelectric technology is an ideal means of harvesting energy from low temperature waste heat that is typically otherwise discarded. The major drawback of this technology is relatively low energy conversion efficiency, barely 10 percent, assuming a temperature differential of 200 Kelvin (K), not including parasitic energy consumption required to keep the other side cold. Rejected heat can be used to fuel an absorption refrigerator and/or to produce domestic hot water in a combined heat and power (CHP) configuration that is able to raise overall system energy efficiency to at least 80 percent. See Figure 21.

The research team also proposed to utilize a low profile economic solar tracker that was recently developed by the principal investigator for utility-scale power plants.[37] The United States Department of Energy (DOE) recently challenged researchers to reduce the installation cost of heliostat fields from $200 to $70 per square meter and to lower total capital costs on utility-scale power plants by 25 percent.[38] The main cost drivers of conventional heliostats in utility-scale power plants are drive motor assemblies, mirror support/structure/foundation, and installation. The research team believed that innovations achieved with advanced utility-scale solar tracker systems could be applied to small-scale CSP systems.

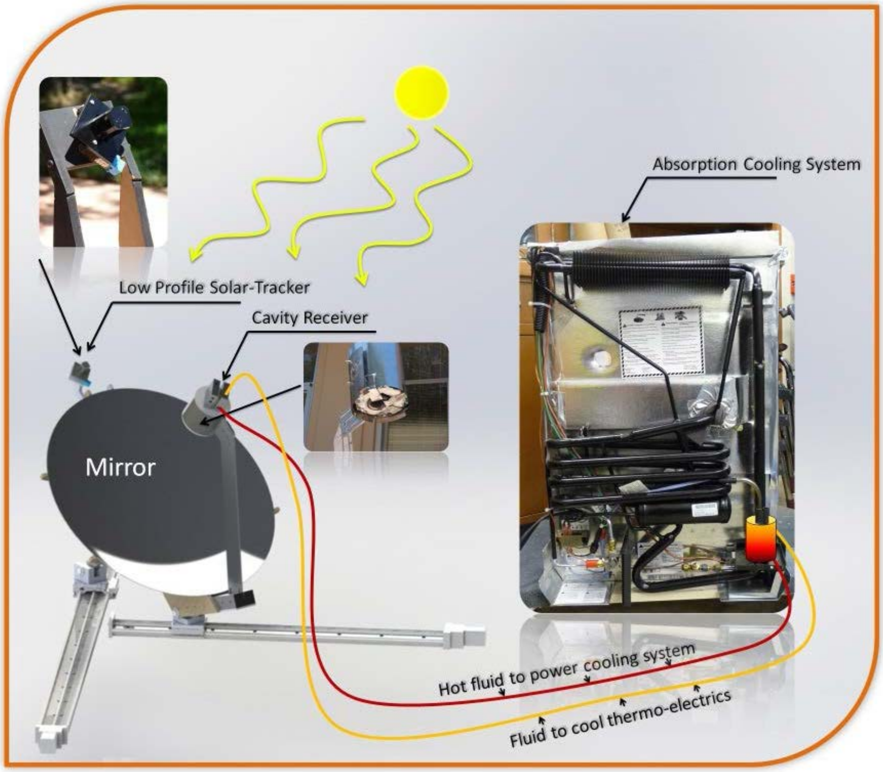
---

36 Rowe DM. CRC handbook of thermoelectrics: CRC Press; 1995

37 Kraemer D, Poudel B., Feng H P., Caylor JC., Yu B., Yan X., et al. High-performance flat-panel solar thermoelectric generators with high thermal concentration. Nat Mater. 2011;10:532-8

38 Sunshot Initiative http://www1.eere.energy.gov/solar/sunshot/index.html. 2012

Figure 21: Schematic of the System Showing the Flow of Energy from the Sun to the Absorption Refrigerator



Practical use of thermoelectric modules has been primarily restricted to niche markets such as space missions, car seat cooling/heating, or other niche industrial applications. Previous research has had limited success, converting less than 5.0 percent of incoming solar energy to useful energy.[39] Subsequent modeling work has predicted conversion efficiencies of at least 10 percent[40] by optimizing the solar concentration ratio. Other studies have predicted conversion efficiency of at least 30 percent can be achieved by using a thermoelectric figure of merit (ZT) of 1.0 or 2.0,[41] which resembles performance levels of large-scale CSP power plants. Most of this work assumes adequate heat dissipation required to keep the cold side of the thermoelectric material at ambient temperature. The amount of heat rejected from thermoelectric modules is typically much greater than power generated. Therefore rejected heat from thermoelectric

39 Kraemer D, Poudel B, Feng H-P, Caylor JC, Yu B, Yan X, et al. High-performance flat-panel solar thermoelectric generators with high thermal concentration. Nature Materials. 2011;10:532-8

40 McEnaney K, Kraemer D, Ren Z, Chen G. Modeling of concentrating solar thermoelectric generators. Journal of Applied Physics. 2011;110:-.

41 Baranowski LL, Snyder GJ, Toberer ES. Concentrated solar thermoelectric generators. Energy & Environmental Science. 2012;5:9055-67

modules can be captured to drive an absorption refrigerator and/or produce hot water to maximize overall energy utilization. A well-designed small-scale CSP system should be optimized to maximize combined efficiency, not simply to maximize power output from the thermoelectric module.

The target energy production from the system was 1.0 kW of electricity and 9.0 kW of rejected useful heat. Generating 1.0 kW of electricity (or 8 kWh per day) is inadequate to meet the daily average home electricity consumption of 50 kWh. Therefore the grid provides supplemental electricity requirements. The proposed system could offset as much as 32 kWh per day if rejected waste heat could be used to replace an electric refrigerator and power an absorption device. Further analysis on the energy balance could help determine optimum working conditions.

The research team successfully fabricated and demonstrated performance of a one-fifteenth (1/15) scale prototype that produced 3.0 watts (W) of electricity and 200 W of heat. See Figure 22. Performance closely matched predictive modeling work. However the experiment was not carried out under optimum conditions. Modeling work suggested that system performance could be significantly improved with better insulation and component modifications. A preliminary economic analysis suggested annual savings of at least $300 for typical residential customers. System cost needs to be reduced further to lower payback to four years. Further work is needed to optimize system design/performance, evaluate manufacturing issues, and validate its financial viability.

Figure 22: Installed Scaled Model of Concentrated Solar Power System

2.16.3G Objectives

The goal of this project was to provide an economically viable, residential-scale concentrated solar power system using thermoelectric modules and a low profile solar tracker. The researchers established the following project objectives:

1. Optimize the solar receiver geometry and build a small-scale prototype that maximizes electric generating efficiency using thermoelectric modules.
2. Measure maximum temperature of a solar receiver within 10 percent of expectations compared to modeling results.
3. Demonstrate maximum power generation of 10 volts (V) under 200 K temperature difference.
4. Implement the use of heat pipes to keep the thermoelectric cold side lower than 400 K.
5. Devise a power control circuit that draws electricity at 50 percent of the open circuit voltage.
6. Demonstrate 300 W of cooling capacity required to operate an absorption refrigerator.
7. Build a heat exchanger that transfers heat from the solar receiver to the absorption refrigerator and achieve working fluid temperature that is within 10 percent of the target value of 380 K.
8. Confirm that the prototype produces 100 W of electricity and 900 W of heat.
9. Demonstrate total daily energy savings of 3 kWh.
10. Develop a business model that demonstrates customer payback of less than four years.

2.16.4G Outcomes

1. Researchers determined that a maximum system efficiency of 35.7 percent could be achieved at a solar concentration of 430 using two thermoelectric modules.
2. The researchers validated computer modeling results by measuring maximum temperature of 590 K which was within 3.3 percent of the theoretical value of 610 K.
3. The researchers measured open circuit voltage of 16.5 V at under less than 200 K temperature difference.
4. The cold side of a thermoelectric module was kept at a temperature lower than 379 K.
5. This task is only 40 percent complete. Researchers uncovered an issue with the power management circuit, preventing measurement of actual open circuit voltage at steady-state conditions. This issue could not be resolved within the time frame of this project.
6. Only 190 W of cooling capacity was demonstrated.
7. The working fluid reached 356 K, which was 6.3 percent below the target value of 380 K.

8. This task is only 50 percent complete. Due to limited access to various mirror sizes, the research team built and tested dish mirrors which were 1/15 and 1/9 scale of targeted design for this project. 3.0 W of electricity and 190 W of heat were produced, matching modeling results.
9. This task is only 20 percent complete. The daily power generation from nine square meters of solar collection area would be approximately 3 kWh of electricity and 12 kWh of heat, which would save consumers at least $300 per year.
10. The researchers completed a bill of materials for completed subcomponents. The final system must cost less than $1,200 for the payoff period to be less than or equal to four years. A detailed bill of materials for the completed tracker and supporting structure showed these prototype subcomponents costing $1,324.

2.16.5G Conclusions

1. The modeling study suggested that the maximum utilization of incoming solar energy of 35.7 percent was achieved with solar concentration of 430.
2. The researchers verified the modeling study with experimental results of maximum temperature within 3.3 percent.
3. Open circuit voltage of 16.5 V exceeded design specifications.
4. It is clearly feasible to maintain the cold side of a thermoelectric module at a low enough temperature.
5. More in-depth research is required to develop a power management circuit for thermoelectric energy harvesting.
6. Demonstrated cooling capacity from waste heat matched computer simulation results fairly accurately at 1/15 system scale. Additional work is needed to optimize system energy balance.
7. The amount of heat transfer collected (190 W) increased by 42 percent using a two-module solar collector system, while the temperature of the fluid measured only 6.3 percent below the target value.
8. Researchers concluded that the proposed modeling work was highly reliable and could be used to engineer and optimize the system.
9. The proposed concept can generate 3 kWh of electricity and 12 kWh of heat per day and save at least $300 per year by modifying the solar concentration up to 700.
10. The system can accommodate mirrors of varying sizes with simple modifications. When the system is scaled up, only the mirror subcomponent will increase in price. The tracker is expected to have installation costs much lower than traditional solar energy systems because the low profile design does not require a concrete foundation or solid steel posts. High temperature thermoelectric modules, silicon carbide receivers, and parabolic

mirrors suitable for this system are not mature technologies and the prototype cost cannot be used to accurately predict the cost of the system under mass production. Further research and the development of dedicated contractors are needed to determine the financial viability of the system.

The research team successfully demonstrated the potential feasibility of using a residential-scale concentrated solar power system that can provide both heat and electricity using thermoelectric modules. Residual heat can be used to produce domestic hot water and/or to operate an absorption refrigerator. The researchers utilized a relatively low cost solar tracker featuring a ceramic cavity receiver for this project. They optimized system parameters to maximize overall system efficiency rather than simply focusing on maximizing the amount of electricity that could be generated. Experimental results validated modeling work suggesting that maximum utilization of incoming solar energy (35.7 percent) can be achieved using a solar concentration of 430, within 3.3 percent of maximum temperature.

Researchers also investigated the potential use of various thermoelectric modules available in the marketplace. Modules from TEG Power generated the largest amount of power and were used for a prototype. Subcomponent testing demonstrated an ability to generate 70 W of electricity and 312 W of heat using a five-foot diameter dish mirror, more than adequate to operate a small refrigerator. Researchers replaced an electric heater on an absorption refrigerator with copper tubes, which received rejected heat from the thermoelectric modules. Performance of the one-fifteenth-scale prototype closely matched modeling results, producing 3 W of electricity and 190 W of rejected heat, even though it was not able to operate under optimum working conditions. The research team believed that the proposed concept could generate 3 kWh of electricity and 12 kWh of heat per day if solar concentration could be increased to 700. This would save residential customers at least $300 per year. The tracker and support systems can accommodate mirrors of different sizes with simple design modifications, allowing the system to be scaled up without drastic cost increases. The thermoelectric and solar thermal collection technologies utilized in this system are premature for the marketplace. Additional work is needed to optimize specification of both components and produce a realistic bill of materials list and associated cost. Researchers believe that a customer payback of four years or less can be achieved with a broad range of combined heat and power products customized for residential, small commercial, and industrial applications.

This project successfully demonstrated proof-of-concept for a small CSP system integrated with a low cost solar tracking device, thermoelectric modules, and an absorption refrigerator.

2.16.6G Recommendations

Additional work is needed to optimize system design, performance, and reliability of each component and the system as a whole. The Program Administrator recommends the following activities:

- Partner with a mirror manufacturer to produce a high temperature mirror for this application.
- Further optimize overall efficiency of the combined heat and power system.

- Investigate low temperature absorption technology to further enhance the flexibility of system design options.
- Explore other potential applications, especially domestic water heating and commercial sterilization.
- Develop more innovative power control circuits for thermoelectric energy harvesting.
- Develop a market/commercialization strategy to estimate system cost and estimate customer payback potential.
- Perform additional product optimization and field testing to validate the performance and reliability of the technology in a working environment.
- Perform a more rigorous cost analysis and business/marketing plan to verify the market potential for this product and ensure that it compares favorably with other devices in the market.
- Test the integrity of the system to ensure that it meets standard industry safety and permitting requirements.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.16.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system. The average single family residential customer in California consumes 6,804 kWh of electricity and uses 454 therms of natural gas per year. Assuming an average price of electricity and natural gas of $0.15 per kWh and $0.94 per therm, respectively, the average annual energy cost for a single-family home is $1,447, the bulk (70 percent) of which is for electricity. The proposed concept was designed to generate about 3 kWh of electricity each day (1,095 kWh per year) and 12 kWh of heat per day (4,380 kWh per year). Waste heat can be used to operate an absorption refrigerator and/or produce hot water.[42] The researchers selected two potential scenarios to demonstrate potential customer value as described below:

<u>Case A - Customer Replaces Electric Refrigerator with Absorption Unit</u>

The assumption for this case is that a customer installs a new CSP system and replaces a worn-out electric refrigerator with a new absorption unit. The CSP system generates 1,095 kWh of electricity per year and lowers electricity demand/use by 750 kWh per year.[43] This reduces electricity purchased from the grid by a total of 1,845 kWh, reducing energy costs by about $277 per year. A typical absorption refrigerator consumes about 130 gallons of propane per year that is equivalent to a heat demand of 3,487 kWh.[44] Therefore the waste heat from the proposed system can meet all the needs of an absorption refrigerator. The remaining 893 kWh of waste heat can then be used to produce hot water that reduces natural gas use by approximately 38 therms, assuming hot water heater appliance efficiency of 70 percent,[45] which is a savings of $44 per year. Total annual energy savings are $321 per year.

<u>Case B - Customer Uses Waste Heat to Product Hot Water</u>

The assumption for this case is that a customer installs a new CSP system, keeps his electric refrigerator and uses all waste heat to product hot water. The CSP system generates 1,095 kWh of electricity per year, reducing energy costs by about $164 per year. All waste heat (4,380 kWh) is used to offset natural gas used to produce hot water. A typical single-family residence uses about 64 gallons of hot water per day[46] or approximately 5,127 kWh of annual hot water heat. Natural gas consumption is reduced by approximately 214 therms, assuming hot water heater appliance efficiency of 70 percent,[47] which is a savings of $201 per year. Total annual energy savings are $365 per year.

In both cases actual customer savings would be somewhat less depending on the annual cost of maintenance for the proposed CSP system. This cost could be more than offset by the potential availability of carbon credits in the future as a result of lower greenhouse gas (GHG) emissions. In addition, the cost of electricity is expected to increase at an annual rate of about 1.7 percent in the state over the next 10 years, according to the California Energy Commission. The proposed

---

42 Overall source efficiency would, in general, be higher if waste heat is used for water heating since the efficiency of an absorption refrigerator is much lower compared to a modern electric appliance.

43 Assumes that a typical residential refrigerator consume 750 kWh per year.

44 http://www.warehouseappliance.com/EZ21SS.html, 2.5 gallons per week x 52 weeks per year

45 (893 kWh x 3,413 Btu/kWh) x (1.0 therm/100,000 Btu)/0.70

46 G. Klein, California Energy Commission,
http://www1.eere.energy.gov/solar/pdfs/sda_saving_water.pdf, slide 8

47 (4,380 kWh x 3,413 Btu/kWh) x (1.0 therm/100,000 Btu)/0.70

system could help offset the need for electricity demand along with the need for new power plant capacity.

2.16.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have not performed a market analysis nor have they surveyed potential customers. They are pursuing Saint Gobain and Kyocera as potential manufacturing and/or distribution partners.

Engineering/Technical

The researchers project that they will need about two years and $250,000 to complete the development of the concept and to build a prototype.

Legal/Contractual

The research team filed a provisional patent (61/904956) on November 15, 2013. The research team is not aware of any potential conflict with existing patents.

Environmental, Safety, Risk Assessments/Quality Plans

There is a potential safety concern about installing a high temperature object on a residential building. This could require additional safety features.

Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization. The research team needs a more cost effective mirror and high temperature thermoelectric device to produce a viable product.

2.17TE Adaptive Electric Vehicle Fast Charging Station

Awardee: Andromeda Power LLC

Principal Investigators: Luigi Giubbolini

2.17.1TE Abstract

Electric vehicle (EV) fast charging stations are highly variable power loads, with power consumption spanning from 55 kilowatts (kW) to three kW during a typical 20 minute charging cycle. This large span puts stress on the grid and creates possible grid failures if multiple stations are operating on the same branch simultaneously. The incurring of demand fees makes the widespread deployment of fast charging stations unfeasible.

To solve these problems, this research team proposed to prove the feasibility of a device, INCEPTIVE (Intelligent Network Controlled Electric Power Terminal to Input the Vehicle Energy), to be integrated into existing fast charging stations. INCEPTIVE provides demand response by communicating with the EV and the grid and optimizing peak charging power from all available energy sources, including alternative sources and backup batteries, while avoiding incurring demand fees on energy from the grid. Its feasibility was demonstrated by the installation of the system into an existing facility equipped with solar panels controlling the operating parameters and performances. The modified charging station embedding INCEPTIVE operated almost daily for a period of eight months without ever crossing the 20 kW demand threshold even when the fast charging station spiked instantaneous demand peaks higher than 50 kW for each session.

The researchers identified two unplanned goals and proved their feasibility during the development of the project. The first was the feasibility of an EV used as local energy storage. The second goal was its integration into the fast charging station to fast charge an EV from another EV. After proving this feasibility, the research team created a new product. This product, called ORCA INCEPTIVE, was engineered to fit inside the trunk of a Nissan Leaf. An EV with ORCA INCEPTIVE is an autonomous rescue vehicle capable of charging a stranded EV in any location without any access to the grid. INCEPTIVE marketing began in July 2014.

Keywords: Demand response, demand control, electric vehicle, fast charging station, renewable energy, CHAdeMO, SAE J1772, photovoltaic, grid-integrated vehicle

2.17.2TE Introduction

Electric vehicles (EVs) are available in the consumer marketplace at price levels competitive with traditional fossil fuel vehicles. In spite of the benefits to consumers and society in terms of maintenance and environmental costs, EV market penetration is hindered due to limitations on mileage range that tends to restrict use to short travel distances. Current EV battery charging systems require hours rather than minutes to recharge for the next use of the vehicle. Although all popular EV battery systems support fast charging in minutes, there is limited available infrastructure to support this feature. If fast charging were readily available, consumer range anxiety could be ameliorated, potentially leading to a significant expansion of EV ownership.

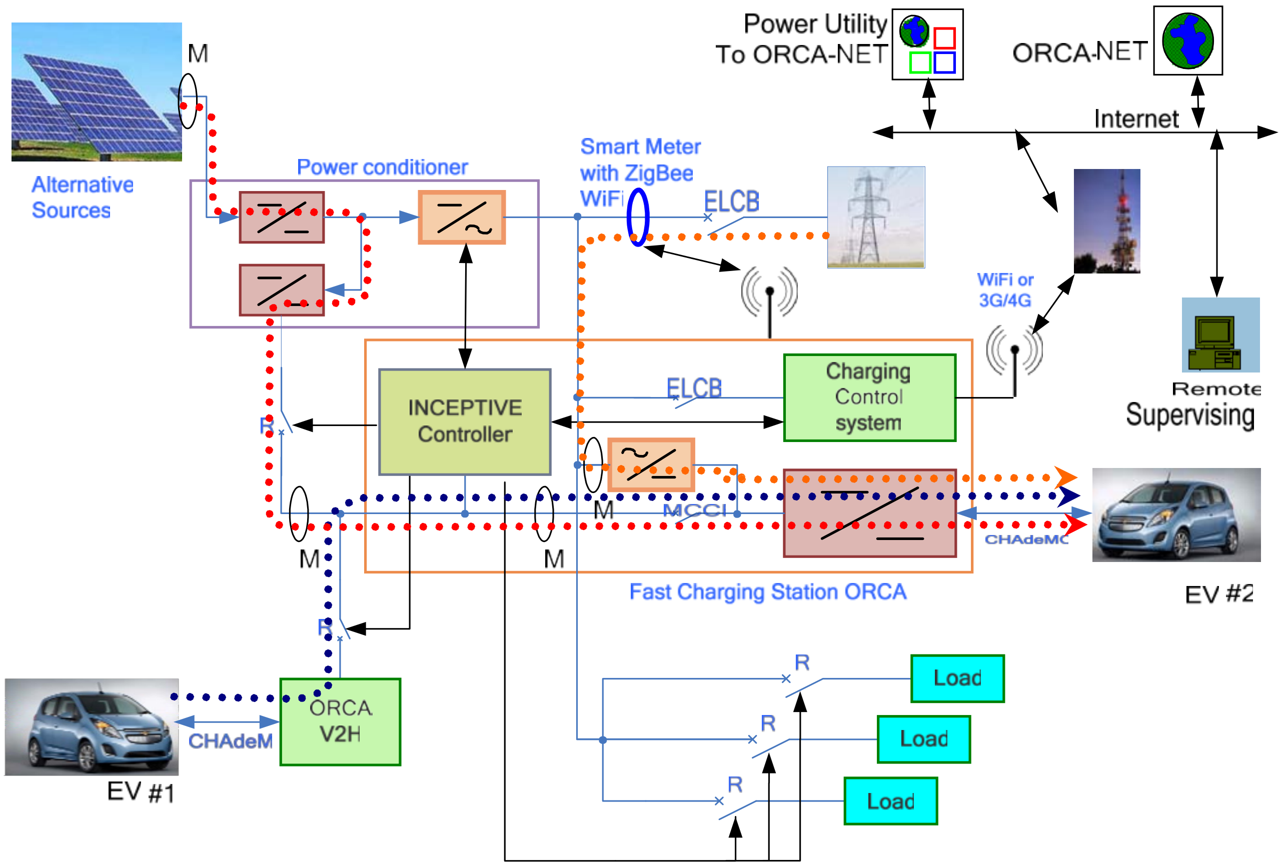
However, EV fast charging stations are highly variable power loads, with power consumption spanning from 55 kW to 3 kW during a typical 20 minute charging cycle. This large span puts stress on the grid and creates possible grid failures if multiple stations are operating on the same branch simultaneously. Of probable greater significance is the incurring of demand fees, which makes it economically unfeasible for widespread deployment of fast charging stations.

To solve these problems the research team proposed to prove the feasibility of a device, INCEPTIVE, to be integrated into an existing fast charging station. INCEPTIVE (Intelligent Network Controlled Electric Power Terminal to Input the Vehicle Energy) provides demand response by communicating with the EV and the grid and optimizing peak charging power from all available energy sources, including alternative sources such as solar, wind, thermal, and backup batteries, while avoiding incurring demand fees on energy from the grid. INCEPTIVE streams energy from alternative sources to smooth the demand rather than loading the grid with demand spikes. This results in obvious benefits for California ratepayers in terms of higher safety, higher infrastructure reliability, and lower maintenance costs.

In addition, the researchers began marketing a mobile fast charging station at an affordable cost. Since it is a transportable charger that needs minimal installation, the ORCA INCEPTIVE was engineered to fit inside the trunk of a Nissan Leaf. An EV with ORCA INCEPTIVE is an autonomous rescue vehicle capable of charging a stranded EV at any location off grid.

Figure 23 shows the comprehensive INCEPTIVE architecture. The Energy Management System (EMS) embedded into the fast charging station ORCA communicates with two EVs and the smart meter merging energy from grid and alternative sources. EV#1 is used as energy storage while the near real-time reading from the smart meter controls the energy and power from the grid to avoid a demand fee.

Figure 23: Implemented Layout of INCEPTIVE



2.17.3TE Objectives

The goal of this project was to determine the feasibility of using an electric vehicle (EV) fast charging station to encourage its integration with alternative sources to avoid peak demand fees.

The project objectives were adjusted in communication with the EISG program manager during the research to add two goals under Objective 4. The research team was able to include assessing the feasibility of an EV as local energy storage (V2L) when a new protocol, CHAdeMO V2L, became available. This protocol allows EVs sold in the United States to be fast discharged using their quick charge port. The team also addressed the feasibility of charging one EV from another. The researchers proposed the following objectives:

1. Conduct lab testing to verify the 20 kW grid limit is not exceeded while producing 50 kW peak charging capacity. This is the main objective of the project, to avoid demand fees.

2. Monitor and record power flow from all sources (solar, battery, and grid) and all loads (EV charging station) to verify that, regardless of EV state of charge and solar radiation, during EV charging:

a. The demand threshold (20 kW) is not exceeded under any circumstances.

b. At least 70 percent of the available power from solar and battery is streamed to the EV before any power is absorbed from the grid.

3. Analyze reports and verification of performance B.1 and B.2 over the period of one month.
4. Conduct lab testing to verify the functionality of:

a. EV energy storage (V2L).

b. EV to EV fast charging station (V2V).

5. Confirm from the project findings that the projected manufacturing cost is less than 10 percent of the fast charging station cost.
6. Confirm from the project findings that the savings provided by the avoidance of demand fees reduces fast charging station operator’s ongoing facility expenses by at least 50 percent.

2.17.4TE Outcomes

1. The research team fabricated one INCEPTIVE prototype and integrated it into one existing fast charging station. The research team verified that the 20 kW grid limit was not exceeded during fast charging with 50 kW peak power capacity.
2. The research team operated the INCEPTIVE system with power supplied from grid, backup battery, and solar panels. The research team verified that the demand threshold of 20 kW was not exceeded and that 90 percent of the available power from solar and battery was streamed to the EV before any power was absorbed from the grid.
3. The research team operated INCEPTIVE almost daily for a period of eight months between October 2013 and May 2014 without ever crossing the 20 kW demand threshold. Demand was always close, but lower than 20 kW, even when the fast charger spiked instantaneous demand peaks higher than 50 kW for each session.
4. The research team verified the feasibility of an EV used as local energy storage. This implementation of energy storage is more convenient in terms of power, energy, and cost than the classic system based on battery backup and inverter that was initially proposed. In addition, the team verified the feasibility of a fast charging station integrated into an EV used as energy storage and source. After proving the feasibility of the new objective, the research team created a new product called ORCA INCEPTIVE. An EV with ORCA INCEPTIVE is an autonomous rescue vehicle capable of charging a stranded EV in any location without any access to the grid.
5. The INCEPTIVE bill of materials confirmed that the manufacturing cost of INCEPTIVE would be lower than 6.0 percent of the cost of ORCA chargers. This low cost is due to the fact that INCEPTIVE was embedded and integrated into the charger using some of

the latter's hardware. For example, the control software of INCEPTIVE was embedded into the charger microprocessor and the communication software in its main processor. The communication through 4G/LTE is a feature already present in the charger. Therefore the processing part of INCEPTIVE did not add any cost.

6. The operation of INCEPTIVE for eight months did not incur any demand fees.

2.17.5TE Conclusions

The research team demonstrated the feasibility of an adaptive EV fast charging station integrated with alternative power sources and able to avoid demand fees. In addition the research team created a new product. This newly developed product, called ORCA INCEPTIVE, was engineered to fit inside the trunk of a Nissan Leaf. An EV with ORCA INCEPTIVE is an autonomous rescue vehicle capable of charging a stranded EV in any location without any access to the grid. INCEPTIVE marketing began in July 2014.

1. The INCEPTIVE prototype was initially tested in the lab, and researchers verified that during operation the threshold of 20 kW was never crossed while producing 50 kW peak charging capacity.
2. The in-field test with solar panels proved the feasibility of EV fast charging stations supplied directly and solely from solar panels and completely isolated from the grid. Therefore the demand threshold of 20 kW was not exceeded under any circumstance.
3. The eight month in-field durability test of INCEPTIVE confirmed, after 193 EV fast charging cycles, the results of the laboratory tests. The demand threshold of 20 kW was never exceeded while producing 50 kW peak power.
4. Development of the INCEPTIVE project validated two additional application ideas for the device: an EV as energy storage and the V2V ORCA INCEPTIVE. This V2V new model of fast charging station can also be used to rescue stranded EVs off grid.
5. The INCEPTIVE bill of materials proved that the incremental cost of the fast charging station is lower than 6.0 percent when it is integrated with INCEPTIVE.
6. The absence of a demand fee proved that the operational cost is 93.8 percent lower than a fast charging station without INCEPTIVE.

2.17.6TE Recommendations

The next logical research objective to advance INCEPTIVE technology is the development and testing of maximum peak power tracking software to manage the issue of variable/intermittent level of available power from solar panels. This effort would make it possible to use INCEPTIVE to charge EVs with energy supplied solely by solar panels.

In addition, emerging research on grid integrated vehicle (GIV) technology from the Vermont Energy Investment Corporation suggests that EVs are capable of serving as energy storage for the grid behind the meter, with EV batteries providing near instantaneous response to grid operator signals. Vehicle to grid (V2G) technology not only offers tremendous opportunity as regulated renewable resources in the wholesale ancillary service markets, but it also makes the grid more reliable, efficient, and cost effective for California ratepayers. The INCEPTIVE technology could be advanced and conveniently used for onboard and offboard grid-integrated vehicles for energy storage application.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.17.7TE Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research is increased use of alternative fuels through increasing the flexibility and usefulness of an electric vehicle to charge from solar energy and to provide an effective grid connection.

INCEPTIVE streams energy from alternative sources to smooth demand rather than loading the grid with demand spikes. This results in benefits for California ratepayers in terms of higher safety, higher infrastructure reliability, and lower maintenance costs. The impact of INCEPTIVE to the electric consumer in terms of savings is important because the smart EV charger encourages use of alternative energy and avoids demand fees. This results in reduced cost for energy purchased by the consumer, emissions reduction, and increased grid reliability.

With the use of INCEPTIVE for eight months, California ratepayers have already benefitted from savings of $13,315.20 (equivalent to about $20,000 per year). This savings reduces the charging station operator’s ongoing facility expenses by a dramatic 93.8 percent, making it possible to operate the fast chargers in a very economical way. If all 468 EV fast chargers in California were equipped with INCEPTIVE, demand fees could be avoided 5,616 times in one year (12 months/year x 468 chargers), with the overall annual cost savings to California ratepayers of about $9.4 million (468 x $20,000).

2.17.8TE Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

During the project the research team created a new product. This product, called ORCA INCEPTIVE, was engineered to fit inside the trunk of a Nissan Leaf. An EV with ORCA INCEPTIVE is an autonomous rescue vehicle capable of charging a stranded EV in any location without any access to the grid. INCEPTIVE marketing began in July 2014.

Engineering/Technical

Researchers estimate that they need about six months and about $30,000 for the CHAdeMO certification process and about $35,000 for the solar power tracker software development.

Legal/Contractual

The researchers did not apply for nor received any patents during this project.

Environmental, Safety, Risk Assessments/ Quality Plans

Product acceptance needs CHAdeMO certification for market penetration and liability reasons. There are no environmental or safety issues other than the obvious ones typical for a high power electrical device made available for public use. These issues are already known and generally covered by the relevant standards in the industry.

Production Readiness/Commercialization

Andromeda Power will manufacture the INCEPTIVE product. INCEPTIVE marketing began in July 2014. The research team created another product called ORCA INCEPTIVE.

2.18TE New Portable Electricity Storage Units Using Nanostructured Supercapacitors

Awardee: University of California, Davis

Principal Investigators: Ning Pan

2.18.1TE Abstract

In this project, researchers developed an electrode fabrication method using vacuum filtration deposition (VFD). They produced supercapacitor electrodes with nickel foam and graphene, a nanoparticle form of carbon. The nickel foam had a mass loading of graphene of about 15 to 25 mg/cm^2. The researchers then processed the electrode cells to further improve their electrochemical performance. They fabricated electrodes and added a selected electrolyte of higher working voltage to produce single supercapacitor cells.

Using electrochemical characterization of each produced cell, the researchers repeatedly increased the energy density of the superconductors from 5 Wh/kg to 10 Wh/kg with conventional organic electrolytes. The researchers calculated the power density to be about 38 kW/kg. The researchers demonstrated that the test cells had a high retention ratio of 99 percent within the first 2,000 charge/discharge cycles. They also demonstrated retention of turnaround efficiency with losses of less than 12.3 percent within 1,000 hours and 32.5 percent within 2,000 hours, respectively. They concluded it is possible to bring down the energy storage cost to 10 cents/farad for active materials.

The researchers combined single cells into final units for overall electric energy with specified voltage and current capacities. The project was successful in demonstrating a new technique for fabricating supercapacitor cells for energy storage.

Keywords: Supercapacitors, enhanced energy capacity, electricity storage/supply unit, graphene nanosheets, vacuum filtration deposition

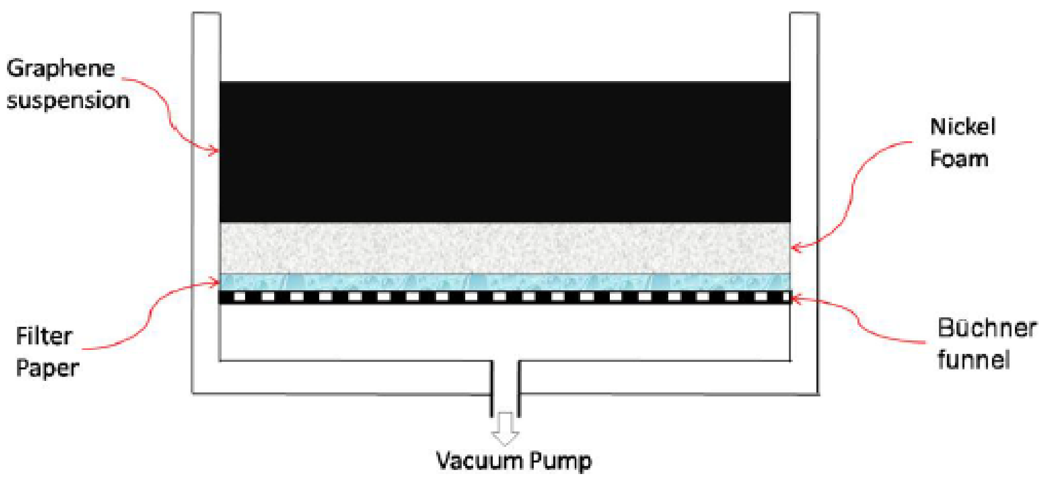
2.18.2TE Introduction

Both stationary and vehicular uses of renewable energy require advanced energy storage capabilities. In stationary applications, storage is necessary to accommodate the intermittency of many renewable energy types like wind and solar. In transportation applications, storage is required to make the energy mobile. To date, energy storage for transportation applications has been heavy or costly or both.

Supercapacitors (SCs) are a promising candidate for power storage cells due to their high power density, reversibility, fast charging time, and long cycle life. Their application has been largely limited by their low energy density, resulting in high total weight for a given amount of storage. The one atom thick carbon material, graphene, is considered by numerous researchers to be a possible working medium to increase the energy storage capacity of SCs. However, the graphene deposit density, or mass loading, produced using traditional electrode fabrication methods so far has resulted in low energy densities.

The goal of this proposed research was to develop fast charging portable electricity storage with controllable discharge rates, using nanostructured supercapacitors with enhanced energy capacity. The researchers developed an innovative electrode fabrication technique to increase the graphene deposit density, its mass loading, on SC electrodes, leading to higher energy density and lower weight. The technique used vacuum filtration. The procedure is illustrated in Figure 24.

Figure 24: Setup for the Vacuum Filtration Deposition Process



2.18.3TE Objectives

The goal of this project was to determine the feasibility of developing a novel processing method involving vacuum filtration deposition (VFD) to fabricate graphene-based nickel foam electrodes for a supercapacitor (SC) to significantly increase its energy storage capacity. The researchers established the following project objectives:

1. Prepare well-dispersed graphene-based suspension and fabricate electrodes with high graphene deposit density of 15—25 mg/cm^2 using nickel foam substrate.
2. Select a suitable electrolyte with higher working voltage around 4—5 V so as to increase the averaged specific capacitance to > 500 F/g.
3. Confirm the proposed approaches are economically feasible to bring down the cost for SCs close to 10 cents/F by mass production.
4. Validate that the energy density of the new units is increased from the conventional SCs of 5 Wh/kg to 10 Wh/kg.
5. Verify decrease of efficiency is smaller than 15 percent within 1,000 hours and 35 percent within 2,000 hours.
6. Analyze all the data collected to assure reduction in specific capacitance < 8.0 percent after 10,000 charge/discharge cycling.

2.18.4TE Outcomes

1. The researchers prepared graphene suspension and fabricated electrodes using the process illustrated in Figure 24. They further treated the electrodes with acid and heat to have three (pristine, acid treated, and heat treated) samples. The researchers characterized the graphene-loaded nickel sponge samples using x-ray and infrared spectroscopy. Scanning electron microscopy showed the graphene was well dispersed. Graphene deposit density ranged from 3.4 to 17.8 mg/cm^2.
2. To achieve higher operating voltage without increasing the cost of the products, the researchers selected an organic electrolyte, lithium hexafluorophosphate in propylene carbonate ($LiPF_6$/PC). The researchers adopted a working voltage of 2.7 V, and calculated an energy density ~ 10 Wh/kg. They achieved a specific capacitance of 152 farads/gram (F/g).
3. The researchers evaluated the material cost for the vacuum-deposited graphene super capacitors. They concluded that the electrolyte cost would likely remain unchanged from conventional supercapacitors, but that it would be possible for the graphene material to be produced at a lower cost, assuming mass production, with a resulting supercapacitor cost of about 10 cents per farad.
4. The researchers measured electrical properties of the single cell supercapacitors in both series connection and parallel connection. They calculated a power density of 38 kW/kg. They estimated the energy density to be 10.1 Wh/kg.
5. The team compared the performance retention ability over time of the two methods using the cyclic voltametry (CV) method for conventional and vacuum-deposited electrodes, each tested 20 days apart. The researchers found that after 20 days the capacitance in the EPD electrodes decreased dramatically, while the vacuum-deposited

cell showed a decrease in efficiency smaller than 12.3 percent within 1,000 hours and smaller than 32.5 percent within 2,000 hours.

6. The researchers measured less than 8.0 percent capacitance reduction after 10,000 charge/discharge cycles for the VFD cells.

2.18.5TE Conclusions

1. The VFD method is a feasible approach to produce supercapacitor electrodes with high graphene density of approximately 18 mg/cm^2 within a nickel foam substrate. The graphene was well dispersed in the nickel foam. The researchers completed this objective.

2. The researchers added some lignin-based carbon fibers into the active material and achieved a specific capacitance 310 F/g, below the proposed target of 500 F/g. They did not complete this objective.

3. The researchers believed that the material cost for SC cells could be cut to 10 cents/F using mass produced graphene. They completed this objective.

4. The calculated energy density from the result was roughly 10.1 Wh/kg, almost double the conventionally produced supercapacitor energy density of 5.2 Wh/kg. The researchers completed this objective.

5. The test cells demonstrated a decrease in efficiency less than 12.3 percent in 1,000 hours and less than 32.5 percent within 2,000 hours. The researchers completed this objective.

6. The VFD-based cells demonstrated less than 8.0 percent capacitance reduction after 10,000 charge/discharge cycles. Cyclic voltametry tests of capacitance and energy density showed efficiency of 90 percent after 2,000 hours. The researchers completed this objective.

While some objectives' parameters were not fully achieved, the researchers demonstrated the feasibility of using vacuum filtration deposition (VFD) to fabricate graphene-based nickel foam electrodes for a supercapacitor (SC) while increasing energy storage capacity.

2.18.6TE Recommendations

The Program Administrator recommends that the researchers:

1. Continue to increase the specific capacitance towards the target of 500 F/gram. This could include extending the lignin additive, use of other additives, use of other electrolytes, and modifying nickel sponge pore size. The researchers should document electrical leakage (phantom loss) from supercapacitor modules fabricated with this technique.

2. Begin mechanical durability assessment, especially for transportation applications subject to vibration. This should be combined with long term testing for longevity approaching at least 17,500 hours (two years) of elapsed time (simulated) and two years

worth of charge/discharge cycling. This is crucial to overcoming the public's perception of short lifetime and expense of battery maintenance and replacement in electric vehicles. Current EVs from Nissan and General Motors have battery warranties of eight years or 100,000 miles.

3. Document fabrication techniques and parameters (e.g., vacuum level) necessary to ensure replicability of performance metrics and incorporate those techniques and parameters into manufacturing guidance.
4. Complete a life cycle cost analysis including materials and cost to manufacture, and determine competitive cost advantages. It is important for the researchers to compare their cost and performance with that of other nanostructured supercapacitors, such as that by Alshareef at Stanford, using MnO_2 and carbon nanotubes.[48]
5. Determine and account for specific safety considerations of short circuit electrical hazards and fire in the event of crashes in transportation applications. This should also include nanoparticle dispersal in the event of crashes.
6. Address safety concerns common to electric vehicles. The researchers should consider cell packing, connections, and other engineering requirements. Further, the use of nanoparticles (graphene) raises worker and public health concerns. Developments in this area should continue to be monitored by the researchers.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.18.7TE Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency

---

48 *High Performance Nanostructured Supercapacitors on a Sponge*, Husam Niman Alshareef, Wei Chen, R B Rakhi, Liangbing Hu, Xing Xie, and Yi Cui, Nano Lett., Publication Date: 16 September 2011. A simple and scalable method has been developed to fabricate nanostructured MnO2-CNTsponge hybrid electrodes. A novel supercapacitor, henceforth referred to as "sponge supercapacitor", has been fabricated using these hybrid electrodes with remarkable performance. Ultrahigh specific capacitance (based on the mass of MnO2) of 1,230 F/g (emphasis added) was achieved, which is close to the theoretical value of MnO2.

- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research is reduced greenhouse gas emissions or reduced health and environmental impacts from transportation-associated air pollution related to electricity and NG production and use

With the reduced cost of energy storage from supercapacitors, electrification of transportation could be accelerated and more quickly and inexpensively achieve California's greenhouse gas emission targets. Reductions of criteria pollutants such as NO_x and reactive organic gasses could also be quickly achieved. The cost effectiveness of numerous California alternative fuels programs[49] could be enhanced, given that the cost per vehicle and associated maintenance costs could be reduced.

For advanced electric vehicles, batteries represent the major cost and major maintenance expense. Using supercapacitors in place of current battery technology and assuming a battery of 25 kWh, an initial cost saving of $3,000 per car could be captured. California accounts for about one third of the electric vehicles sold in the United States with just fewer than 100,000 vehicles in 2013. If 70 percent of those cars used supercapacitors instead of batteries, California residents could save over $200 million. Those savings could be higher as more electric vehicles were sold and if existing EV owners replaced worn-out batteries with superconductors.

Estimating the amount of greenhouse gas and criteria pollutant emission reduction that could occur is too speculative at this time. The absolute amount would likely be unchanged from the baseline of battery-powered electric vehicles but could be achieved sooner, depending on the penetration rate. Some small but unquantified increase in total electric vehicles could be achieved if potential purchasers are at the decision margin and have high demand elasticity.

2.18.8TE Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers had not performed a market analysis nor had they contacted potential customers by the end of this project. They had discussed the project with a potential investor who could help them take this technology to market

49 See, for example, the 34 incentive programs and 37 laws and regulations described at http://www.afdc.energy.gov/laws/all?state=CA .

Engineering/Technical

The researchers estimate that they can complete product development and demonstration in less than three years with an additional $500,000 in funding.

Legal/Contractual

The researchers have completed a self-search and have not identified any conflicting patents. They have not received or applied for patents but are working with the University of California at Davis Research Office on patent protection and assignment.

Environmental, Safety, Risk Assessments/ Quality Plans

Significant work remains to be accomplished in this area.

Production Readiness/Commercialization

The product is not quite ready for production. While awaiting engineering and technical specification development and manufacturing scale-up, commercialization efforts (primarily early stage marketing and partner development) can begin.

2.19TE Flexible Inverter for Electric Accessories and Export Power in Trucks

Awardee: Motiv Power Systems

Principal Investigators: Jim Castelaz

2.19.1TE Abstract

This research demonstrated the feasibility of a prototype three-phase inverter module that can operate as an accessory motor controller, provide alternating current export power, and interact with the electrical grid. The flexible inverter incorporates a wide operating voltage range and automotive-grade chassis, with the goal of compatibility with a wide variety of medium and heavy duty electric vehicle applications. The researchers successfully completed testing of the inverter with demonstration of grid interactivity up to 10 kW per inverter module, with limited motor drive capability and export power generation.

Keywords: Electricity, inverter, three phase export power, automotive-grade inverter, grid interactive export power, accessory motor drive, printed circuit board

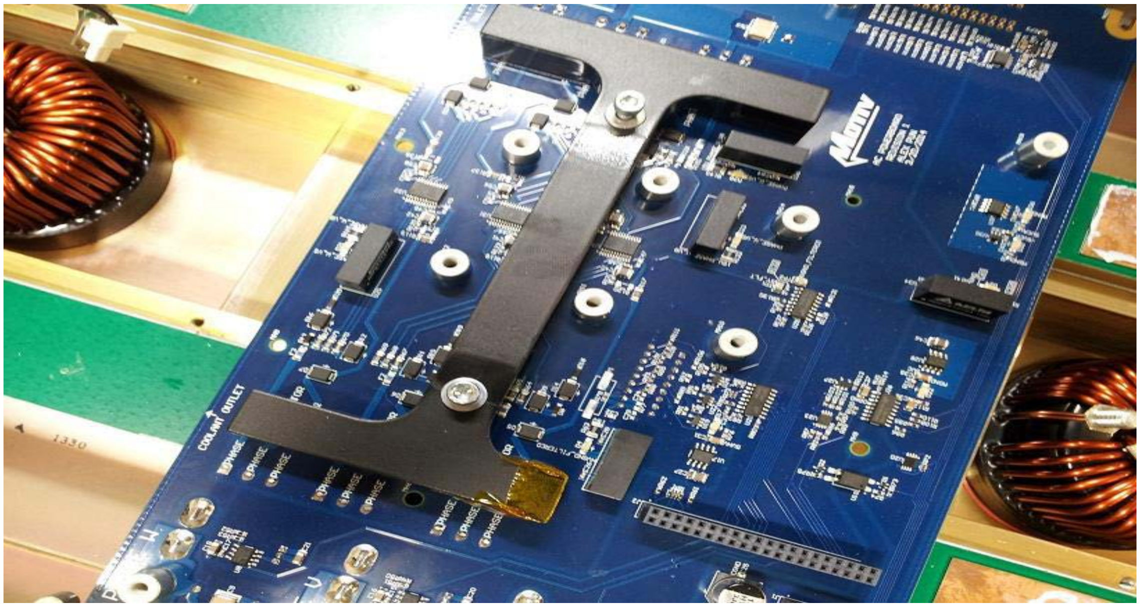
2.19.2TE Introduction

In research sponsored by the California Energy Commission, the CalHEAT research center study titled “Vehicle and Technologies Characterization and Baseline” found electrification of truck accessories and grid-interactive export power are both critical to meeting California’s goals of reducing energy use and air pollution from the medium and heavy duty fleet. The goal of this project was to solve this problem by demonstrating the feasibility of an advanced automotive-grade inverter.

Deploying such an inverter could have significant public benefits stemming from a potential 2.0 percent to 5.0 percent fuel use reduction for repowering the operation of vehicle electrical accessories. Since there are 1.5 million of these vehicles on the road in California, the average savings for each equipped vehicle could be 77 to 193 gallons per year, or roughly $300 to $770 per year (assuming $4/gallon for diesel fuel). Medium and heavy duty vehicles in California produce 29.68 million metric tons of CO_2 equivalent (MMT CO_2e) greenhouse gases, so this reduction is equivalent to 0.6 to 1.5 MMT CO_2e. Diesel generators produce additional air pollutants of NO_x+NMHC at 7.5 g/kWh (Tier 2) or 4.7 g/kWh (Tier 3). Using the vehicles to generate this power (stored in batteries and charged by the grid) on site would eliminate nearly all of these emissions, since the grid is 200 to 600 times cleaner than portable diesel generators.

The proposed inverter would advance present technology as it would provide an economically viable product that would have scalable power capability and be able to drive accessory motors. It would also provide alternating current (AC) export power and interact with the AC line to enable charging and vehicle-to-grid (V2G) applications. See Figure 25.

Figure 25: Inverter Board after Installation into DC-DC Converter Chassis



2.19.3TE Objectives

The goal of this project was to determine the feasibility of a prototype three-phase inverter module that can operate as an accessory motor controller, provide alternating current export power, and interact with the electrical grid.

The research team intended to prove the feasibility of a new type of inverter that could achieve all of the above requirements over a large voltage range with scalability up to very high power levels. The approach taken in the development of the inverter differs from other market offerings in several key ways. First, it uses a pre-existing rugged chassis that can carry a number of power processing phases. This allows for power scalability that can reduce current ripple by allowing for phase interleaving of the individual inverter elements. The inverter is thereby more economical by leveraging the volumes of the enclosure already used for an automotive grade DC-DC converter. The platform incorporates software control directly to the gates of the power processing elements so that the same power processing engine can be configured for operation as a standalone inverter, grid tied inverter, or as a motor drive. The inverter is designed with 1,200 volt (V) switches and capacitors rated over one kilovolt (kV) to allow for working voltages up to 800 V. This provides compatibility with a wide range of common vehicle battery constructions and chemistries, from 340 V lithium ion packs to sodium nickel chemistries at 580 V, as well as series-parallel combinations of these types. The inverter includes a 32 bit micro controller with automotive peripherals to communicate over several standard automotive buses including controller area network (CAN). The inverter could be controlled by any CAN or FlexRay-based vehicle controller.

The researchers established the following project objectives:

1. Verify the design will achieve five metrics via simulation
    a. Power 10 kW
    b. Line regulation ± 2.0 percent (stand-alone)
    c. Load regulation ± 2.0 percent
    d. Response bandwidth > 100 Hz
    e. Voltage ripple < 2.0 percent
2. Prototype the design using enclosure, printed circuit board (PCB) mounting, control PCB, cooling, and test setup components that are already being manufactured
3. Perform prototype testing to verify the following:
    a. The five simulation metrics listed in Objective 1
    b. Motor drive efficiency > 94 percent
    c. Export power efficiency > 93 percent
    d. Conformance to grid interactivity standards

e. Agreement between the simulation of Objective 1 and test results

4. Simulate the multi-module inverter to verify 40 kW power capability
5. Confirm from the project findings the projected manufacturing cost of $500/kW
6. Confirm that the projected life cycle cost of export power over the vehicle's life of $0.15/kWh continues to be supported
7. Confirm the projected life cycle value of ancillary grid services from grid interactivity is $6,000 to $10,000 per year for a four-module inverter

2.19.4TE Outcomes

The researchers achieved the following project outcomes:

1. Simulation results showed the following:
    a. 10.8 kW output power.
    b. Line regulation of 0.3 percent.
    c. Load regulation of 2.0 percent.
    d. Response bandwidth of roughly 660 Hz.
    e. Voltage ripple in export power mode of 0.73 percent.
2. The design was successfully prototyped with enclosure, PCB mounting, control PCB, and cooling used in automotive-grade DC-DC converters.
3. Prototype testing demonstrated metrics from Objective 1 as follows:
    a. Operation up to 3.6 kW real power and 10.8 kilovolt amperes (kVA) reactive power
    b. Line regulation of 1.0 percent.
    c. Load regulation -3.3 percent.
    d. Response bandwidth of 412.5 Hz.
    e. 2.0 percent voltage ripple in grid-tied mode and 3.1 percent ripple in open loop mode.

    Motor drive efficiency of 94 percent could not be verified.

    Export power efficiency of 93.5 percent.

    Grid interactivity standards were verified per selected sections of IEEE1547.

    Waveforms showed qualitative agreement with simulation results.

    The researchers did not perform quantitative comparative analysis.

4. Simulation results for four parallel connected inverter modules showed:
    a. Output power of 38 kW
    b. Line regulation of 1.76 percent
    c. Load Regulation of 2.24 percent
    d. Response bandwidth of roughly 275 Hz
    e. Voltage ripple of 1.4 percent
5. A manufacturing breakdown indicated the current costs to produce the inverter were $327.58 per kW. This is expected to come down to $147.21 per kW as board production is scaled up.
6. The researchers could not confirm the projected life cycle cost of export power over the vehicle's life of $0.15 per kWh at current battery costs. They projected export power costs to be $0.247/kWh. This is lower than that of diesel generators but only provides savings of from of $0.6 to $0.16 per kWh.
7. The projected life cycle value of ancillary grid services from grid interactivity was $5,000—$7,500 per year for a vehicle utilizing the four-module inverter, slightly lower than the project objective.

2.19.5TE Conclusions

The researchers encountered a number of circumstances that limited findings. Nonetheless, they demonstrated the potential feasibility of a flexible inverter capable of operating in all three of the requested operating modes. They developed and tested software controls with switchable modes to accommodate motor control, export power, and grid interactivity. Simulation indicated that it is possible to scale such an inverter to higher power levels.

1. Simulation results for a single module were in good agreement with the initial estimates. The simulation step was valuable for the basic component sizing and feasibility but did not include subtle effects that showed up during the test process. This led to the simulation predicting over four times lower ripple and three times better line regulation than was achieved during testing. This was in part due to the smaller filter capacitors that were used during testing.
2. Using the existing enclosure did not present any difficulties during laboratory analysis. For commercialization, additional modifications will need to be made to the enclosure to accommodate larger magnetics. However the cooling and control interface worked seamlessly with the new power processing PCB. Overall, using the same hardware for motor drive and AC power delivery would allow economics of scale not available in other inverter products.
3. The majority of the testing gave positive results. The achieved power level indicated that grid export power capability up to 40 kW could be packaged in an enclosure suitable for

mounting on medium to heavy duty trucks and buses. The efficiency result for export power was favorable and indicated the inverter is deployable in cases where high efficiency is a key metric.

Not all of the objectives were achieved. One performance deficit was in load regulation. The test showed a -3.3 percent voltage deviation for a 5 amp (A) load, a drop that can be expected to increase proportionally as the load is increased to the full 30 A. In simulation this was addressed by implementing a feedback loop that regulated the sensed voltage at the output of each module. This could eliminate the regulation issue at the expense of increased software complexity. A smaller output filter could also improve load regulation but would also increase ripple.

The most substantial issue encountered during the testing was in the motor control mode. The motor speed achieved in the testing was 800 RPM. This motor typically runs at 2,700 RPM for compressor drive applications. Testing could not be accomplished at this level because the simple V/Hz drive was not able to lock onto the required three-phase voltage without significant tuning.

The motor control algorithm used was not sophisticated enough to provide the speed and power level necessary for a good efficiency measurement. This was due to inadequate time scheduled for algorithm development and excessive reliance on unverified simulation data. The sensing was in place to provide for a more complex control than the V/Hz control method, but time was not available for algorithm development.

4. Load regulation did not meet the original objectives, but this miss was only by a few tenths of a percent.
5. Manufacturing cost analysis came out well within the initial projected manufacturing costs of $500/kW. Cost analysis indicated the inverter could improve its marketability in the next few years, assuming the cost of battery degradation and the true costs per kWh are reduced.
6. The initial cost objectives were not achieved, with the estimate approximately $0.09 per kWh over the initial specification. Battery price and cycle degradation were the primary drivers of the additional life cycle cost.
7. Fleet managers have the potential for significant savings by selling the regulation capacity provided by these vehicle-mounted inverters to utilities. Regulation provides the majority of the anticipated $5,000—$7,000 in yearly savings.

2.19.6TE Recommendations

The Program Administer recommends the following actions:

- Improve the motor control software and validating operation of accessory motors at full power and full speed.

- Add increased functionality to the export power mode so that the software will compensate for voltage drop in the output filter. This has the potential to greatly improve the load regulation.
- Improve the efficiency of inverters. Currently over 12 percent of the energy is lost in power conversion. This is significant given the high cost of energy storage.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.19.7TE Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research is reduced greenhouse gas emissions or reduced health and environmental impacts from transportation-associated air pollution related to electricity and NG production and use.

For the vehicle energy consumption reduction, the CalHEAT *Vehicle and Technologies Characterization and Baseline* study published in January 2011 cites a 2.0 percent to 5.0 percent fuel reduction for electrified accessories. The medium- and heavy-duty truck fleet in California uses 5.8 billion gallons of diesel annually. With 100 percent market penetration, this savings could be 116 million to 290 million gallons of fuel. Since there are 1.5 million of these vehicles on the road in California, the average savings for each equipped vehicle could be 77 to 193 gallons per year, or roughly $300 to $770 per year (assuming $4/gallon for diesel fuel). Medium- and heavy- duty vehicles in California produce 29.68 million metric tons of CO_2 equivalent (MMT CO_2e) greenhouse gases, so this reduction is equivalent to 0.6 to 1.5 MMT CO_2e. Diesel generators produce additional air pollutants of NO_x+NMHC at 7.5 g/kWh (Tier 2) or 4.7 g/kWh (Tier 3). Using the vehicles to generate this power (stored in batteries and charged by the grid) on site could eliminate nearly all of these emissions, since the grid is 200 to 600 times cleaner than portable diesel generators.

Finally, for the value of grid ancillary services, this inverter configured with four modules could provide 40 kW for grid regulation. This is valued between $5,000 and $7,000 annually. Once this product is commercialized and installed on even a few fleets, this savings could also represent a significant benefit to California, its residents, and ratepayers because it potentially eliminates the need to build additional peak load generating resources. For example, an order of 100 trucks (a feasible size for a large fleet owner such as UPS) with installed four-module inverters represents 4 MW of potential regulation power.

2.19.8TE Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

Motiv Power Systems was seeking to purchase a similar system prior to development and was unable to find one for use in all electric vehicles. This system will be integrated into Motiv's electric power control system for use in medium- to heavy-duty electric vehicle applications including school buses, refuse trucks, and shuttle buses.

Engineering/Technical

The researchers state they can complete a full demonstration in about one year with a relatively small amount of funding.

Legal/Contractual

The researchers have no patents or any active applications related to this research. The team prefers to address this technology as a trade secret.

Environmental, Safety, Risk Assessments/ Quality Plans

The researchers will need to address these plans as they specify a product.

Production Readiness/Commercialization

While the potential feasibility has been demonstrated, the product is not ready for commercialization and requires additional development. There is no known commercialization plan. The research team indicated that the product can be added to Motiv's set of power electronics modules that are already being installed on vehicles.

2.20TE High Capacity Energy Storage for Locomotive Hybridization

Awardee: Peaker Conversions

Principal Investigators: Dave Cook

2.20.1TE Abstract

Researchers in this project tested the feasibility of using large banks of ultracapacitor (UC) cells for capturing braking energy installed on commuter passenger trains. The project involved research, building prototypes, and durability testing.

The researchers built an air-cooled test fixture to operate six 3,000 farad (F) cells to test set-up durability. They cycled the ultracapacitor bank 71,000 times from charged to discharged. At the end of the test, one cell still had 85 percent of its original capacity and four additional cells were still being cycled but had deteriorated to 50 percent capacity. The researchers stated several of the test cells were damaged during the development of the test stand, and durability results were inconclusive.

The researchers estimated that new packaging, material improvements, and a wider voltage operating range would result in a cost of storage of approximately $27,000 per kWh.

The researchers calculated that a commuter train on the Caltrain Peninsula route would need 45 kWh of energy capacity and that the use of ultracapacitor hybridization could reduce the energy used to propel the train by more than 50 percent, provided the issue of durability could be resolved.

Hybridizing commuter trains with heavy start/stop cycling would also reduce the emissions of both criteria pollutants and greenhouse gases in proportion to the reduction in energy use.

Keywords: Locomotive, hybrid, commuter, ultracapacitor, supercapacitor, regenerative braking

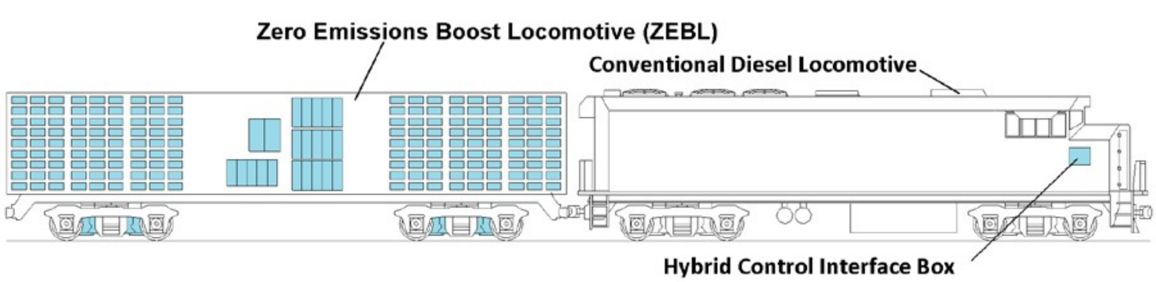
2.20.2TE Introduction

Energy efficiency, including in transportation applications, remains a high priority policy in California. Commuter rail is saving California significant amounts of fuel compared to single occupant vehicles or ride-sharing uses. Commuter rail could be even more competitive if the tremendous amounts of energy lost to friction in braking could be captured and beneficially used. Some estimates put the amount of braking energy that could be captured at approximately 50 percent of a train's total energy consumption. The percent of energy potentially captured depends upon the ratio of braking for passenger stops and acceleration away from stops and cruising. While those factors would vary by route, the amounts are significant.

Regenerative braking captures the energy of braking rather than losing it to friction heat buildup of traditional brake shoes and drums. Regenerative braking systems can store the energy as battery charge or a spinning flywheel. Battery charge suffers from cycle life limitation and low power density, while flywheels suffer from high cost and durability as well as space considerations. Busy commuter trains can make up to 100 stop/start cycles a day. Batteries are typically rated for a cycle life of 2,000 to 10,000 cycles. At 100 cycles a day, even the best battery system at 10,000 cycles would have to be replaced every four months. A promising alternative is to store regenerative braking energy as electrical charge in ultracapacitors (UC). Ultracapacitors are being used in transit busses for storing braking energy, but those applications have significantly less energy requirements than for much heavier commuter trains. A typical transit bus may have about 0.5 kWh of onboard storage, while calculations indicate a commuter train would require about 80 kWh of storage.

One significant challenge to ultracapacitor use in systems of this scale is the high cost per unit of energy storage and maintaining temperature control for up to 40,000 ultracapacitor cells. In this project, researchers tested the feasibility of a simplified UC cell module racking system with forced air cooling. This would allow the individual UC cells to operate over a wider voltage range, allowing a smaller number of UC cells for a given amount of stored energy, thus reducing the cost per kilowatt-hour (kWh) of energy storage in the system. The ultracapacitor system would be used in conjunction with a traditional locomotive. The basic concept is shown in Figure 26.

Figure 26: Zero Emissions Boost Locomotive and Hybrid Control Interface Box



2.20.3TE Objectives

The goal of this project was to determine the feasibility of using banks of ultracapacitors (UC) to capture braking energy to reduce train energy use. The researchers established the following project objectives:

1. Design and build a test stand that will control and measure the charge/discharge rates of the ultracapacitor cells, the cell cooling airflow mass and temperature, and the individual cell voltages.
2. Verify that air flow and pressure drop are within +/- 3.0 percent of the design set point.
3. Verify that UC outer cell temperature is below 100° C while cycling on commuter duty.
4. Verify that UC cells will not degrade below 80 percent of original capacitance in 100,000 cycles when operating at 2.9 volts peak.
5. Verify that an 85 kWh system can be built for under $35,000 per kWh.
6. Verify that no UC cell is below 90 percent capacitance at 50 percent of cycles.
7. Verify that no UC cell is below 80 percent capacitance at final test cycles.

2.20.4TE Outcomes

1. The researchers designed and built a test stand that could test two strings of ultracapacitors in parallel. They completed 80 percent of a second test stand that could test three times as many cells at twice the electrical current rating and that incorporated a pair of eight horsepower direct current motors to simulate locomotive drive systems.
2. The researchers designed and built a prototype spiral cooling sleeve. They performed an air flow test with results falling within 10 percent of the target design point.
3. The researchers confirmed through measurement that the cells did not heat up more than 20° C over ambient temperature or a total of 45° C, with air pressure and flow at .20 of the design point.
4. The researchers reduced the initial target peak voltage for testing from 2.9 volts to 2.7 volts. They determined that one or more cells were damaged during the development of the test stand electronics. Specifically, one cell dropped below 80 percent capacity. That cell was kept in testing to characterize its continued deterioration.
5. The researchers designed several modules for cost estimating purposes. They calculated a price of $27,000 per kWh including a 25 percent markup to cover overhead.
6. The researchers cycled the six cells for 50,000 cycles. At this point the researchers had already replaced one cell at approximately 18,000 cycles. The researchers determined that the five original cells and one replacement cell were operating at a consistent minimum voltage with various levels of deterioration, as indicated in Table 4.

Table 4: Cell Capacity after 50,000 Cycles

Cell	Capacity After 50,000 Cycles
1	(replaced)
2	50 percent
3	50 percent
4	50 percent
5	85 percent
6	50 percent

7. The researchers continued testing and reported measurements until approximately 65,000 cycles. They determined that while each test cell was deteriorating, and deteriorating by different mechanisms and rates, capacity of all six cells stayed above 50 percent.

2.20.5TE Conclusions

1. The researchers built a test stand capable of cycle testing ultracapacitor cells that could control and measure the charge/discharge rates of the ultracapacitor cells, the cell cooling air flow mass and temperature, and the individual cell voltages. The researchers completed this objective.

2. It was possible to design air flow systems with air flow amounts and pressure drop within tolerance of the design points. The researchers completed this objective.

3. The cell outer temperature was measured at approximately 45° C when operated in cycling mode, below the objective metric of 100° C. The researchers completed this objective.

4. Five of the six cells degraded to less than 85 percent, with four cells at 50 percent. One cell was replaced due to premature damage. The researchers completed this task but did not meet the performance objective.

5. The calculated cost of $27,000 per kWh was below the performance objective of $35,000. Final cost is uncertain until durability issues are resolved. The researchers completed this objective.

6. Every cell failed to meet the performance objective of retaining 90 percent of capacity after 50 percent of cycles (in this instance 50,000 of 100,000 target cycles) with four of six degrading to approximately 50 percent of capacity. The researchers completed this task, but did not meet the performance objective.

7. Every cell failed to meet the performance objective of retaining 80 percent of capacity after 100,000 cycles with four of six degrading to approximately 50 percent of capacity. The research ended at 65,000 cycles. The researchers did not meet this objective.

The researchers did not demonstrate the feasibility of their concept based upon the established performance objective. They did show the feasibility of specific elements, such as the air cooling scheme to maintain ultracapacitor cell temperature under transit-like cycling and the estimated energy storage costs. Durability remains uncertain.

2.20.6TE Recommendations

The Program Administrator recommends that the researchers:

1. Determine failure modes and causes and evaluate mechanisms for the capacity degradation found. The researchers should work with ultracapacitor manufacturers to resolve causes of degradation.
2. Evaluate operational voltages and the impact of lowering operating voltages on durability, costs, and capacity of ultracapacitor cells.
3. Develop operator guidance for systems' replacement as degradation proceeds, allowing operators to decide between partial operation of ultracapacitors and fuel savings. This should be done as a function of diesel fuel price. An operator faced with low future prices (such as today's under $3 per gallon) may have a different decision matrix than one faced with high future fuel price (such as last year's near $4 per gallon).
4. Develop methods and protocols for testing and replacing cells or modules if degradation is occurring in only a few cells or banks of cells.
5. Continue larger scale testing as full-scale banks of ultracapacitors will have different heat buildup and heat transfer properties than the test stand.
6. Test the system of temperature and charge/discharge controls in a test stand that replicates the operational environment of a commuter train (e.g., vibration).
7. Document the quality assurance requirements for individual ultracapacitors and banks and determine the cost tradeoffs for slight degradation of quality versus perfect quality.
8. Demonstrate durability to the original performance objectives of 90 percent at 50,000 cycles and 80 percent at 100,000.
9. Partner with locomotive companies and/or train operators to demonstrate the full-scale feasibility of this concept.
10. Resolve potential patent conflict as soon as possible. There is a small risk of patent conflict when connecting the ultracapacitor locomotive with the traditional diesel locomotive.
11. Document the comparative economics on a life cycle basis once the performance of the ultracapacitor concept has been full demonstrated and documented.
12. Develop quality metrics and quality assurance protocols for potential suppliers that consider the cost tradeoffs inherent in higher levels of quality.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the

Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.20.7TE Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research is improved transportation energy efficiency.

Basic hybridization of commuter locomotives, including regenerative braking, could result in up to 50 percent reduction in energy used by commuter rail agencies, directly reducing the current railroad diesel fuel consumption. As an example, Metrolink consumes 7.4 million diesel gallons per year. If the Metrolink fleet were hybridized, savings of approximately 2.6 million gallons of diesel per year could be realized. In 2012 Metrolink's average fuel cost was $3.68 per diesel gallon. A 35 percent savings on those 7.4 million gallons would be a fuel cost saving of $9.5 million per year. As of December 2014 diesel prices in California, net of state and federal road tax, was $3.10 per gallon, which would calculate to a potential saving of just over $8 million per year.

2.20.8TE Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have received expressions of interest from Maxwell Technologies, a supplier of ultracapacitors. They have not completed a market assessment.

Engineering/Technical

The researchers estimated they will need approximately $4 to $7 million and one year to complete a technology demonstration of this concept.

Legal/Contractual

The researchers have applied for two provisional patents and one utility patent.

Environmental, Safety, Risk Assessments/ Quality Plans

The cost effectiveness and train operator acceptance of this concept will depend significantly on the lifetime of the ultracapacitor banks, which is reliant on the quality of the ultracapacitors.

Production Readiness/Commercialization

The concept is not yet ready for commercialization.